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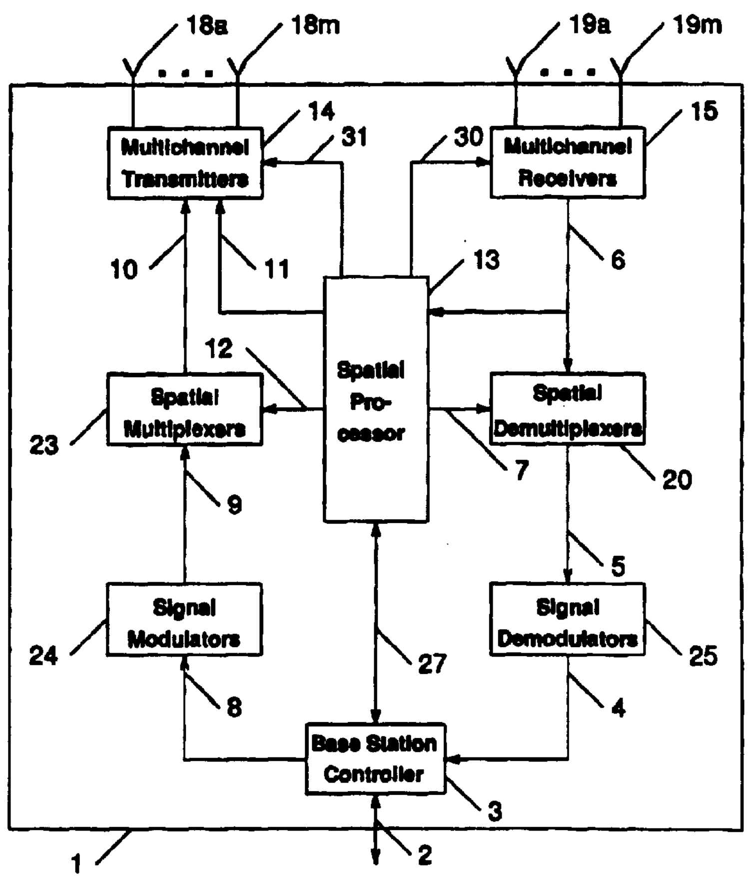
(57) Abstract

A wireless system includes a network of base stations (1) for receiving uplink signals transmitted from a plurality of remote terminals (69) and for transmitting downlink signals to the remote terminals. Each base station (1) includes a plurality of transmitting antenna elements (18) for transmitting downlink signals and receiving antenna elements (19) for receiving uplink signals, a signal processor (13) connected to the antenna elements for determining spatial signatures and multiplexing and demultiplexing functions. A multiple base station controller (66) is used for optimizing network performance.



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SPECTRALLY EFFICIENT HIGH CAPACITY WIRELESS COMMUNICATION SYSTEMS

Background of the Invention

This invention relates to wireless communication systems and, more particularly, to using antenna arrays and signal processing to dramatically increase the capacity and performance of wireless communication systems.

Wireless communication systems can be used to complement and in some instances replace conventional wired communication systems in areas where conventional wire-line systems are unavailable, unreliable, or excessively expensive. Examples of such areas are: rural areas with a small number of widespread users, underdeveloped areas with little or no current infrastructure, reliability sensitive applications in areas where wired infrastructure is unreliable, and political environments where monopolistic wired service providers maintain artificially high prices. Even in metropolitan areas and highly developed countries, wireless communication systems may be used for low-cost ubiquitous communication, new flexible data services, and emergency communication systems. In general, wireless communication systems may be used for voice communications just like conventional telephone systems, and for data communications in a radio-based wide area or local area network as well.

Wireless users access wireless communication systems using remote terminals such as cellular telephones and data modems equipped with radio transceivers. Such systems (and in particular the remote terminals) have protocols for initiating calls, receiving calls, and general transfer of information. The information transfer can be performed in real-time such as is the case for circuit-switched voice conversations and faxes, or in a store-and-forward manner such as is often the case for electronic mail, paging and other similar message transfer systems.

Wireless communication systems are generally allocated a portion of the radio frequency spectrum for their operation. The allocated portion of the spectrum is divided up into communication channels. These channels may be distinguished by frequency, by time, by code, or by some combination of the above. Each of these communication channels will be referred to herein as *conventional channels*. Depending on the available frequency allocations, the wireless system might have from one to several hundred communication channels. To provide full-duplex communication links, typically some of the communication channels are used for communication from base stations to users' remote terminals (the downlink), and others are used for communication from users' remote terminals to base stations (the uplink).

Wireless communication systems generally have one or more radio base stations, each of which provide coverage to a geographic area known as a cell and often serve as a point-of-presence (PoP) providing connection to a wide area network such as a Public Switched Telephone Network (PSTN). Often a predetermined subset of the available communication channels is assigned to each radio base station in an attempt to minimize the amount of interference experienced by users of the system. Within its cell, a radio base station can communicate simultaneously with many remote terminals by using different conventional communication channels for each remote terminal.

As aforementioned, base stations can act as PoPs, providing connection to one or more wired communication systems. Such systems include local data networks, wide area data networks, and PSTNs. Thus, remote users are provided access to local and/or wide area data services and the local public telephone system. Base stations can also be used to provide local connectivity without direct access to a wired network such as in local area emergency and mobile battlefield communication systems. Base stations can provide connectivity of various kinds as well. In the aforementioned examples, point-to-point communications where roughly equal amounts of information flow in both directions between two users were assumed. In other applications such as interactive television, information is broadcast to all users simultaneously, and responses from many of the remote units are to be processed at the base stations.

However, conventional wireless communication systems are comparatively spectrally inefficient. In conventional wireless communication systems, only one remote terminal can use any one conventional channel within a cell at any one time. If more than one remote terminal in a cell attempts to use the same channel at the same time, the downlink and uplink signals associated with the remote terminals interfere with each other. Since conventional receiver technology can not eliminate the interference in these combined uplink and downlink signals, remote terminals are unable to communicate effectively with the base station when interference is present. Thus, the total capacity of the system is limited by the number of conventional channels the base station has available, and in the overall system, by the way in which these channels are re-used among multiple cells. Consequently, conventional wireless systems are unable to provide capacity anywhere near that of wired communication systems.

Summary of the Invention

Accordingly, an object of the present invention is to use antenna arrays and signal processing to separate combinations of received (uplink) signals. Another object of the present invention is to transmit spatially multiplexed downlink signals. The result is a dramatic increase in spectral efficiency, capacity, signal quality, and coverage of wireless communication systems. Capacity is increased by allowing multiple users to simultaneously share the same conventional communication channel within a cell without interfering with one another, and further by allowing more frequent reuse of the same conventional channel within a geographic area covering many cells. Signal quality and coverage area are improved through intelligent processing of signals received from and transmitted by multiple antenna elements. Moreover, a further object of the present invention is to provide capacity gains by dynamically allocating conventional channels among base stations and remote terminals.

Briefly, the invention comprises antenna arrays and signal processing means for measuring, calculating, storing, and using ***spatial signatures*** of receivers and transmitters in wireless communication systems to increase system capacity, signal quality, and coverage, and to reduce overall system cost. The antenna array and signal processing means can be employed at base stations (PoPs) and remote terminals. Generally there can be different processing requirements at base stations where many signals are being concentrated than at remote terminals where in general only a limited number of communication links are being managed.

As an example, in a wireless local loop application, a particular base station might serve as a PoP for many remote terminals and employ the antenna array and signal processing described herein. Additionally, remote terminals could employ antenna arrays and signal processing to further improve their capacity and signal quality over simpler remote terminals that handle fewer communication links. Herein, the distinction between base stations and remote terminals is that base stations generally act as concentrators connecting

to multiple remote units simultaneously, possibly providing a high capacity connection to a wide area network. While for the sake of clarity much of the ensuing discussion is couched in terms of simple remote terminals that do not employ antenna arrays, nothing herein should be interpreted as preventing such an application. Thus, while hereafter spatial signatures will be associated primarily with remote terminals, when antenna arrays are employed at remote terminals, base stations will have associated spatial signatures as well.

Briefly, there are two spatial signatures associated with each remote terminal/base station pair on a particular frequency channel, where for the purpose of this discussion it is assumed that only base stations have antenna arrays. Base stations associate with each remote terminal in their cell a spatial signature related to how that remote terminal receives signals transmitted to it by the base station's antenna array, and a second spatial signature related to how the base station's receive antenna array receives signals transmitted by the remote terminal. In a system with many conventional channels, each remote terminal/base station pair has transmit and receive spatial signatures for each conventional channel.

The receive spatial signature characterizes how the base station antenna array receives signals from the particular remote unit in a particular conventional channel. In one embodiment, it is a complex vector containing responses (amplitude and phase with respect to a reference) of each the antenna element receivers, *i.e.*, for an m-element array,

$$\mathbf{a}_{br} = [\mathbf{a}_{br}(1), \mathbf{a}_{br}(2), \ldots, \mathbf{a}_{br}(m)]^T, \tag{1}$$

where $\mathbf{a}_{br}(i)$ is the response of the i^{th} receiver to a unit power transmitted signal from the remote terminal. Assuming that a narrowband signal $s_r(t)$ is transmitted from the remote terminal, the base station receiver outputs at time t are then given by

$$\mathbf{z}_b(t) = \mathbf{a}_{br} s_r(t-\tau) + \mathbf{n}_b(t), \tag{2}$$

where τ accounts for the mean propagation delay between the remote terminal and the base station antenna array, and $\mathbf{n}_b(t)$ represents noise present in the environment and the receivers.

The transmit spatial signature characterizes how the remote terminal receives signals from each of the antenna array elements at the base station in a particular conventional channel. In one embodiment, it is a complex vector containing relative amounts (amplitude and phase with respect to a reference) of each the antenna element transmitter outputs that are contained in the remote terminal receiver output, *i.e.*, for an m-element array,

$$\mathbf{a}_{rb} = [\mathbf{a}_{rb}(1), \mathbf{a}_{rb}(2), \ldots, \mathbf{a}_{rb}(m)], \tag{3}$$

where $\mathbf{a}_{rb}(i)$ is the amplitude and phase (with respect to some fixed reference) of the remote terminal receiver output for a unit power signal transmitted from the i^{th} element in the base station array. Assuming that a vector of complex signals $\mathbf{s}_b = [\mathbf{s}_b(1), \ldots, \mathbf{s}_b(m)]^T$ were transmitted from the antenna array, the output of the remote terminal receiver would be given by

$$z_r(t) = \mathbf{a}_{rb}\mathbf{s}_b(t-\tau) + n_r(t), \tag{4}$$

where $n_r(t)$ represents noise present in the environment and the receiver. These spatial signatures are calculated (estimated) and stored at each base station for each remote terminal in its cell and for each conventional channel. For fixed remote terminals and base stations in stationary environments, the spatial

signatures can be updated infrequently. In general, however, changes in the RF propagation environment between the base station and the remote terminal can alter the signatures and require that they be updated. Note that henceforth, the time argument in parentheses will be suppressed; integers inside parentheses will be used solely for indexing into vectors and matrices.

In the previous discussion, temporally matched receivers and transmitters were assumed. If there are differences in the temporal responses, these can be equalized using temporal filtering techniques as is well-known. Furthermore, the channel bandwidths were assumed to be small compared to the center frequency of operation. Large bandwidth channels may require more than one complex vector to accurately describe the outputs as is well known.

When more than one remote terminal wants to communicate at the same time, the signal processing means at the base station uses the spatial signatures of the remote terminals to determine if subsets of them can communicate with the base station simultaneously by sharing a conventional channel. In a system with m receive and m transmit antenna elements, up to m remote terminals can share the same conventional channel at the same time.

When multiple remote terminals are sharing a single conventional uplink channel, the multiple antenna elements at the base station each measure a combination of the arriving uplink signals and noise. These combinations result from the relative locations of the antenna elements, the locations of the remote terminals, and the RF propagation environment. The signal processing means calculates spatial demultiplexing weights to allow the uplink signals to be separated from the combinations of uplink signals measured by the multiple antenna elements.

In applications where different downlink signals are to be sent from the base station to the remote terminals, the signal processing means computes spatial multiplexing weights that are used to produce multiplexed downlink signals, which when transmitted from the antenna elements at the base station result in the correct downlink signal being received at each remote terminal with appropriate signal quality.

In applications where the same signal is to be transmitted from the base station to a large number (more than the number of antenna elements) of remote terminals, the signal processing means computes weights appropriate for broadcasting the signal, covering the area necessary to reach all the remote terminals.

Therefore, the signal processing means facilitates simultaneous communication between a base station and multiple remote terminals on the same conventional channel. The conventional channel may be a frequency channel, a time slot in a time division multiplexed system, a code in a code division multiplexed system, or any combination of the above.

In one embodiment, all elements of a single antenna array transmit and receive radio frequency signals, while in another embodiment the antenna array includes separate transmit antenna elements and receive antenna elements. The number of transmit and receive elements need not be the same. If they are not the same, the maximum number of point-to-point links that can simultaneously be established in one conventional channel is given by the smaller of the two numbers.

The invention and objects and features thereof will be more readily apparent from the following detailed description together with the figures and appended claims.

Brief Description of The Drawings

Figure 1 is a functional block diagram of a base station in accordance with the invention.

Figure 2 is a functional block diagram of multichannel receivers in the base station.

Figure 3 is a functional block diagram of a spatial demultiplexer in the base station.

Figure 5 is a functional block diagram of a multichannel transmitter in the base station.

Figure 6 is a functional block diagram of a spatial processor in the base station.

Figure 7 is a functional block diagram of a remote terminal with a transponder switch.

Figure 8 is a functional block diagram of a remote terminal.

Figure 9 is a schematic diagram of a network system comprised of three base stations and a multiple base station controller.

List of Reference Numerals

1. base station
2. base station communication link
3. base station controller
4. demodulated received signal
5. spatially separated uplink signals
6. received signal measurements
7. demultiplexing weights
8. data to be transmitted directionally
9. modulated signal to be multiplexed for transmission
10. modulated, spatially multiplexed signals to be transmitted
11. calibration signals to be transmitted
12. multiplexing weights
13. spatial processor
14. multichannel transmitters
15. multichannel receivers

16a. multichannel receiver
16m. multichannel receiver
17a. multichannel transmitter
17m. multichannel transmitter
18a. transmit antenna
18m. transmit antenna
19a. receive antenna
19m. receive antenna
20. spatial demultiplexer
21. adder
22a. multipliers
22m. multipliers
23. spatial multiplexer
24. signal modulator
25. signal demodulator
26a. multipliers
26m. multipliers
27. spatial control data
28. spatial parameter data
29. common receiver oscillator
30. receiver control data
31. transmitter control data
32. common transmitter oscillator

33. spatial processor controller
34. active remote terminal list
35. channel selector
36. remote terminal database
37. spatial weight processor
38. spatial signature processor
39. remote terminal antenna
40. remote terminal duplexer
41. remote terminal duplexer output
42. remote terminal receiver
43. remote terminal received signal
44. remote terminal received calibration signal
45. remote terminal demodulator
46. remote terminal demodulated data
47. remote terminal keyboard and keyboard controller
48. remote terminal keyboard data
49. remote terminal display data
50. remote terminal display and display controller
51. remote terminal modulator
52. remote terminal data to be transmitted
53. remote terminal modulated data to be transmitted
54. remote terminal transmitter
55. remote terminal transmitter output
56. remote terminal transmitter control data
57. remote terminal receiver control data
58. remote terminal microphone
59. remote terminal microphone signal
60. remote terminal speaker
61. remote terminal speaker signal
62. remote terminal central processing unit
63. remote terminal transponder switch
64. remote terminal transponder switch control
65. wide area network
66. multiple base station controller

67a. cell boundary

67b. cell boundary

67c. cell boundary

68. high speed message link
69. remote terminal

Description of Invention

Figure 1 depicts the preferred embodiment of a base station 1. A base station controller 3 acts as an interface between base station 1 and any external connection via a base station communication link 2, and serves to coordinate the overall operation of base station 1. In the preferred embodiment, base station controller 3 is implemented with a conventional central processing unit and associated memory and programming.

Incoming or uplink radio transmissions impinge on an antenna array composed of a number, m, of receive antenna elements 19(a,...,m) each of whose outputs is connected to one of m multichannel receivers in a bank of phase-coherent multichannel receivers 15. Multichannel receivers 15 have well-matched amplitude and phase responses across the frequency bands of interest, or, as is well known, correction filters are implemented to account for any differences.

The illustrative embodiment describes a conventional frequency division multiple access system. Each multichannel receiver is capable of handling multiple frequency channels. The symbol N_{cc} will be used to reference the maximum number of conventional frequency channels that can be handled by the receivers. Depending on the frequencies allocated for the operation of the wireless communication system and the bandwidths chosen for particular communication links, N_{cc} could be as small as one (a single frequency channel) or as large as thousands. In alternate embodiments, multichannel receivers 15 might instead handle multiple time slots, multiple codes, or some combination of these well known multiple access techniques.

In each conventional channel, receive antenna elements 19(a,...,m) each measure a combination of the arriving uplink signals from the remote terminals sharing this conventional channel. These combinations result from the relative locations of the antenna elements, the locations of the remote terminals, and the RF propagation environment, and for narrowband signals are given by equation (2).

Figure 2 depicts individual multichannel receivers 16(a, ...,m) with antenna element connections, common local receiver oscillators 29, one for each conventional frequency channel to be used at that base station, and received signal measurements 6. Common local receiver oscillators 29 ensure that the signals from receive antenna elements 19(a, ...,m) are coherently down-converted to baseband: its N_{cc} frequencies are set so that multichannel receivers 16(a, ...,m) extract all N_{cc} frequency channels of interest. The frequencies of common local receiver oscillators 29 are controlled by a spatial processor 13 (figure 1) via receiver control data 30. In an alternate embodiment, where multiple frequency channels are all contained in a contiguous frequency band, a common local oscillator is used to downconvert the entire band which is then digitized, and digital filters and decimators extract the desired subset of channels using well known techniques.

The illustrative embodiment describes a frequency division multiple access system. In a time division multiple access or code division multiple access system, common oscillators 29 would be augmented to relay common time slot or common code signals respectively from spatial processor 13, via receiver control data 30, to multichannel receivers 16(a, ...,m). In these embodiments, multichannel receivers 16(a, ...,m) perform selection of conventional time division channels or conventional code division channels in addition to down conversion to baseband.

Referring again to Figure 1, multichannel receivers 15 produce received signal measurements 6 which are supplied to spatial processor 13 and to a set of spatial demultiplexers 20. In this embodiment, received signal measurements 6 contain m complex baseband signals for each of N_{cc} frequency channels.

Figure 6 shows a more detailed block diagram of spatial processor 13. Spatial processor 13 produces and maintains spatial signatures for each remote terminal for each conventional frequency channel, and calculates spatial multiplexing and demultiplexing weights for use by spatial demultiplexers 20 and spatial multiplexers 23. In the preferred embodiment, spatial processor 13 is implemented using a conventional central processing unit. Received signal measurements 6 go into a spatial signature processor 38 which estimates and updates spatial signatures. Spatial signatures are stored in a spatial signature list in a remote terminal database 36 and are used by channel selector 35 and spatial weight processor 37, which also produces demultiplexing weights 7 and multiplexing weights 12. A spatial processor controller 33 connects to spatial weight processor 37 and also produces receiver control data 30 transmitter control data 31 and spatial control data 27.

Referring again to Figure 1, spatial demultiplexers 20 combine received signal measurements 6 according to spatial demultiplexing weights 7. Figure 3 shows a spatial demultiplexer 20 for a single conventional channel. In this embodiment, arithmetic operations in spatial demultiplexer 20 are carried out using general purpose arithmetic chips. In figure 3, $\mathbf{z}_b(i)$ denotes the i^{th} component of received signal measurement vector 6 for a single conventional channel, and $\mathbf{w}^*_{rx}(i)$ denotes the complex conjugate of the i^{th} component of the spatial demultiplexing weight vector 7 for a remote terminal using this conventional channel.

For each remote terminal on each conventional channel, the spatial demultiplexer 20 computes the inner-product of the spatial demultiplexing weights 7 for the conventional channel with the received signal measurements 6:

$$\mathbf{w}^*_{rx}\mathbf{z}_b = \mathbf{w}^*_{rx}(1)\mathbf{z}_b(1) + \ \ldots \ + \mathbf{w}^*_{rx}(m)\mathbf{z}_b(m), \tag{5}$$

where $(\cdot)^*$ indicates complex conjugation, numbers inside parentheses indicate element number (*e.g.*, $\mathbf{w}_{rx}(i)$ is the i^{th} component of the vector $\mathbf{w}_{rx}$), the multiplication is performed by multipliers 22(a, ...,m), and the addition is performed by adder 21. For each remote terminal on each conventional channel, the output of adder 21 given by equation (5) comprises the spatially separated uplink signals 5.

Referring again to Figure 1, the outputs of spatial demultiplexers 20 are spatially separated uplink signals 5 for each remote terminal communicating with the base station. Spatially separated uplink signals 5 are demodulated by signal demodulators 25, producing demodulated received signals 4 for each remote terminal communicating with the base station. Demodulated received signals 4 and corresponding spatial control data 27 are available to base station controller 3.

In embodiments where channel coding of the signals sent by remote terminals is performed, base station controller 3 sends the demodulated received signals 4 to spatial processor 13 which, using well known decoding techniques, estimates Bit-Error-Rates (BERs) and compares them against acceptable thresholds stored in the remote terminal database 36. If the BERs are unacceptable, spatial processor 13 reallocates resources so as to alleviate the problem. In one embodiment, links with unacceptable BERs are assigned to new channels using the same strategy as adding a new user with the exception that the current channel is not acceptable unless the current set of users of that particular channel changes. Additionally, recalibration of the receive signature for that remote terminal/base station pair is performed when that conventional channel is available.

For transmission, signal modulators 24 produce modulated signals 9 for each remote terminal the base station is transmitting to, and a set of spatial multiplexing weights 12 for each remote terminal are applied

to the respective modulated signals in spatial multiplexers 23 to produce spatially multiplexed signals to be transmitted 10 for each of the m transmit antennas 18(a,...,m) and each of the N_{cc} conventional channels.

In the illustrative embodiment the number N_{cc} of downlink conventional channels is the same as the number N_{cc} of uplink conventional channels. In other embodiments, there may be different numbers of uplink and downlink conventional channels. Furthermore, the channels may be of different types and bandwidths as is the case for an interactive television application where the downlink is comprised of wideband video channels and the uplink employs narrowband audio/data channels.

Additionally, the illustrative embodiment shows the same number of antenna elements, m, for transmit and receive. In other embodiments, the number of transmit antenna elements and the number of receive antenna elements may be different, up to and including the case where transmit employs only one transmit antenna element in an omnidirectional sense such as in an interactive television application.

Figure 4 shows the spatial multiplexer for one remote terminal on a particular conventional channel. Arithmetic operations in spatial multiplexer 23 are carried out using general purpose arithmetic chips. The component of modulated signals 9 destined for this remote terminal on this conventional channel is denoted by s_b, and $\mathbf{w}_{tx}(i)$ denotes the i^{th} component of spatial multiplexing weight vector 12 for this remote terminal on this conventional channel.

For each remote terminal on each conventional channel, the spatial multiplexer 23 computes the product of its spatial multiplexing weight vector (from the spatial multiplexing weights 12) with its modulated signal s_b (from the modulated signals 9):

$$\mathbf{w}_{tx}^{*} s_b = \begin{bmatrix} \mathbf{w}_{tx}^{*}(1) s_b \\ \vdots \\ \mathbf{w}_{tx}^{*}(m) s_b \end{bmatrix}, \tag{6}$$

where $(\cdot)^{*}$ indicates complex conjugate (transpose) and the multiplication is performed by multipliers 26(a, ...,m). For each conventional channel, equation (6) is evaluated by the spatial multiplexer 23 for each remote terminal that is being transmitted to on this conventional channel. Corresponding to each remote terminal is a different multiplexing weight vector and modulated signal. For each conventional channel, spatial multiplexer 23 adds the spatially multiplexed signals for each remote terminal being transmitted to on this conventional channel, producing modulated and spatially multiplexed signals 10 that are the signals to be transmitted for each conventional downlink channel from each antenna.

Modulated and spatially multiplexed signals 10 are inputs to a bank of m phase coherent multichannel transmitters 14. Multichannel transmitters 14 either have well-matched amplitude and phase responses across the frequency bands of interest, or, as is well known, correction filters are implemented to account for any differences. Figure 5 depicts multichannel transmitters 17(a, ...,m) with antenna connections, common local transmitter oscillators 32, and digital inputs 10. Common local transmitter oscillators 32 ensure that the relative phases of spatially multiplexed signals 10 are preserved during transmission by transmit antennas 18(a, ...,m). The frequencies of common local transmitter oscillators 32 are controlled by spatial processor 13 (see figure 1) via transmitter control data 31.

In an alternate embodiment, spatial multiplexer 23 uses well known baseband multiplexing techniques to multiplex all the calculated conventional channel signals to be transmitted into a single wideband signal to be upconverted and transmitted by each of the multichannel transmitters 17(a, ...,m). The multiplexing can be performed either digitally or in analog as appropriate.

The illustrative embodiment shows a system with multiple frequency channels. In a time division multiple access or code division multiple access system, common oscillators 32 would be augmented to relay common time slot or common code signals respectively from spatial processor 13, via transmitter control data 31, to multichannel transmitters 17(a, ...,m).

Referring again to figure 1, in applications where transmit spatial signatures are required, spatial processor 13 is also able to transmit predetermined calibration signals 11 for each antenna on a particular conventional downlink channel. Spatial processor 13 instructs multichannel transmitters 17(a, ...,m), via transmitter control data 31, to transmit predetermined calibration signals 11 in place of spatially multiplexed signals 10 for a particular conventional downlink channel. This is one mechanism used for determining the transmit spatial signatures of the remote terminals on this conventional downlink channel.

In alternate embodiments where well known channel coding techniques are used to encode the signals to be transmitted to remote terminals, remote terminals employ well known decoding techniques to estimate BERs which are then reported back to the base station on their uplink channel. If these BERs exceed acceptable limits, corrective action is taken. In one embodiment, the corrective active involves reallocating resources by using the same strategy as adding a new user with the exception that the current channel is not acceptable unless the current set of users of that particular channel changes. Additionally, recalibration of the transmit signature for that remote terminal/base station pair is performed when that conventional channel is available.

Figure 7 depicts the component arrangement in a remote terminal that provides voice communication. The remote terminal's antenna 39 is connected to a duplexer 40 to permit antenna 39 to be used for both transmission and reception. In an alternate embodiment, separate receive and transmit antennas are used eliminating the need for duplexer 40. In another alternate embodiment where reception and transmission occur on the same frequency channel but at different times, a transmit/receive (TR) switch is used instead of a duplexer as is well known. Duplexer output 41 serves as input to a receiver 42. Receiver 42 produces a down-converted signal 43 which is the input to a demodulator 45. A demodulated received voice signal 61 is input to a speaker 60.

Demodulated received control data 46 is supplied to a remote terminal central processing unit 62 (CPU). Demodulated received control data 46 is used for receiving data from base station 1 during call setup and termination, and in an alternate embodiment, for determining the quality (BER) of the signals being received by the remote terminal for transmission back to the base station as described above.

Remote terminal CPU 62 is implemented with a standard microprocessor. Remote terminal CPU 62 also produces receiver control data 57 for selecting the remote terminal's reception channel, transmitter control data 56 for setting the remote terminal's transmission channel and power level, control data to be transmitted 52, and display data 49 for remote terminal display 50. Remote terminal CPU 62 also receives keyboard data 48 from remote terminal keyboard 47.

The remote terminal's voice signal to be transmitted 59 from microphone 58 is input to a modulator 51. Control data to be transmitted 52 is supplied by remote terminal CPU 62. Control data to be transmitted 52 is used for transmitting data to base station 1 during call setup and termination as well as for transmitting information during the call such as measures of call quality (*e.g.*, bit error rates (BERs)). The modulated signal to be transmitted 53, output by modulator 51, is up-converted and amplified by a transmitter 54, producing a transmitter output signal 55. Transmitter output 55 is then input to duplexer 40 for transmission by antenna 39.

In an alternate embodiment, the remote terminal provides digital data communication. Demodulated received voice signal 61, speaker 60, microphone 58, and voice signal to be transmitted 59 are replaced by digital interfaces well-known in the art that allow data to be transmitted to and from an external data processing device (for example, a computer).

Referring again to figure 7, the remote terminal allows received data 43 to be transmitted back to base station 1 via switch 63 controlled by remote terminal CPU 62 through switch control signal 64. In normal operation, switch 63 drives transmitter 54 with modulated signal 53 of modulator 51. When the remote terminal is instructed by base station 1 to enter calibration mode, remote terminal CPU 62 toggles switch control signal 64, which instructs switch 63 to drive transmitter 54 with received data 43.

Figure 8 shows an alternate embodiment of the remote terminal calibration function. Switch 63 of figure 7 is no longer used. Instead, the output of receiver 42 is supplied to remote terminal CPU 62 by data connection 44. In normal operation remote terminal CPU 62 ignores data connection 44. In calibration mode, remote terminal CPU 62 uses data connection 44 to compute the remote terminal's transmit spatial signature, which is transmitted back to base station 1 through modulator 51 and transmitter 54 as control data to be transmitted 52.

In an alternate embodiment, special calibration procedures in the remote terminal are not required. In many conventional wireless protocol standards, remote terminals regularly report received signal strength or receive signal quality back the base station. In this embodiment, the received signal strength reports are sufficient to compute the remote terminal's transmit spatial signature, as described below.

Operation of Invention

General Principles — Base Station

In many respects, the spectrally efficient base station shown in figure 1 behaves much like a standard wireless communication system base station. The primary distinction is that the spectrally efficient base station supports many more simultaneous conversations than it has conventional communication channels. The conventional communication channels may be frequency channels, time channels, code channels, or any combination of these. The spatial multiplexer/demultiplexer increases the system capacity by allowing multiple spatial channels on each of these conventional channels. Moreover, by combining signals from multiple receive antennas, the spatial demultiplexer 20 produces spatially separated uplink signals 5 that have substantially improved signal-to-noise, reduced interference, and improved quality in multipath environments compared to a standard base station.

In the illustrative embodiment, a wireless communication system comprised of multiple remote terminals and base stations incorporating antenna arrays and spatial signal processing is described. Such systems have application, for example, in providing wireless access to the local PSTN. Information transfers (or calls) are initiated by either a remote terminal or by communication link 2 through base station controller 3. Call initialization takes place on a downlink and uplink control channel as is well known in the art. In the present embodiment, the downlink control channel is transmitted using transmission antennas 18(a,. . . ,m). In an alternate embodiment, the downlink control channel is broadcast from a single, omnidirectional antenna. Base station controller 3 passes the identification of the remote terminal to be involved in the call to spatial processor 13 which uses the stored spatial signatures of that remote terminal to determine which conventional communication channel the remote terminal should use. The selected channel may already be occupied by several remote terminals, however spatial processor 13 uses the spatial signatures of all of

the remote terminals on that channel to determine that they can share the channel without interference. In a system with m receive and m transmit antenna elements, up to m remote terminals can share the same conventional channel. More generally, the number of point-to-point full-duplex communication links that can occupy the same conventional channel at the same time is given by the smaller of the number of receive and transmit elements.

Spatial processor 13 uses calculated spatial multiplexing and demultiplexing weights for the selected channel and the remote terminal in question to configure spatial multiplexer 23 and spatial demultiplexer 20. Spatial processor 13 then informs controller 3 of the selected channel. As in a conventional base station, controller 3 then commands the remote terminal (via the downlink control channel) to switch to the selected channel for continued communications. In the event that the remote terminal has power control capabilities, as is well known in the art, controller 3 also commands the remote terminal to adjust its power to an appropriate level based on parameters such as the power levels of the other remote terminals sharing the same conventional channel and the required signal quality for each link as discussed below. At the termination of communications, the remote terminal returns to its idle state where it monitors the downlink control channel awaiting its next call. This frees up that "spatial channel" for another remote terminal.

Spatial Processing — Base Station

Figure 6 shows a block diagram of spatial processor 13. It is controlled by spatial processor controller 33, which interfaces to base station controller 3 via link 27. Spatial processor controller 33 controls the gain and frequency settings of multichannel transmitters 14 and multichannel receivers 15 by control lines 31 and 30.

Spatial processor 13 maintains an active remote terminal list 34 that catalogs which remote terminals are currently using each conventional communication channel as well as their current transmit power levels. Other parameters of the remote terminals such as modulation formats currently used, receiver noise levels in current frequency channels, and current signal quality requirements are stored as well. Spatial processor 13 also maintains a spatial signature list in the remote terminal database 36, which in alternate embodiments includes remote terminals' power control levels, allowed conventional frequency channels for receive and transmit, and list of modulation formats understood.

The spatial signature list in the remote terminal database 36 contains a transmit spatial signature, $\mathbf{a}_{rb}$, and a receive spatial signature, $\mathbf{a}_{br}$, for every frequency of operation for each remote terminal. In another embodiment, estimates of the quality (*e.g.*, estimate error covariances) of the spatial signatures are stored as well. As aforementioned, the transmit spatial signature, $\mathbf{a}_{rb}$, for a particular remote terminal and a particular frequency channel is defined as the vector of relative complex signal amplitudes that would be seen arriving at that particular remote terminal as a result of identical (equal amplitude and phase) unit power narrow band signals, at that particular frequency, being transmitted through multichannel transmitters 14 and transmission antennas 18(a, ...,m). The transmit spatial signature includes the effects of the propagation environment between the base station and the remote terminal, as well as any amplitude and phase differences in multichannel transmitters 14, antenna cables, and transmission antennas 18(a, ...,m). The receive spatial signature, $\mathbf{a}_{br}$, for a particular remote terminal and a particular frequency channel, is defined as the vector of complex signal amplitudes that would be measured at the outputs of

multichannel receiver 16 given a single unit power narrow band signal being transmitted by that particular remote terminal, at that particular frequency.

When the base station controller 1 forwards a call initialization request for a particular remote terminal via link 27, a channel selector 35 searches active remote terminal list 34 to find a conventional communication channel that can accommodate the remote terminal. In the preferred embodiment, there is a receive active remote terminal list and a transmit active remote terminal list which are used by channel selector 35 in forming both a multiplexing and a demultiplexing spatial signature matrix for each conventional channel. For each conventional channel, the columns of the demultiplexing and rows of the multiplexing spatial signature matrices are the stored receive and transmit spatial signatures of each of the remote terminals currently active on (using) that channel plus one more column containing the appropriate spatial signature of the remote terminal requesting a communication channel.

The multiplexing spatial signature matrix for each channel, $A_{rb,p}$ (where p denotes the conventional channel number), is formed using transmit spatial signatures as shown in equation (7):

$$A_{rb,p} = \begin{bmatrix} \mathbf{a}^1_{rb,p} \\ \vdots \\ \mathbf{a}^{n_p}_{rb,p} \end{bmatrix}, \tag{7}$$

where $\mathbf{a}^i_{rb,p}$ is the transmit spatial signature for i^{th} remote terminal assigned to channel p and n_p is the total number of remotes on conventional channel p.

The demultiplexing spatial signature matrix, $A_{br,p}$, is formed using receive spatial signatures as shown in equation (8):

$$A_{br,p} = [\mathbf{a}^1_{br,p}, \mathbf{a}^2_{br,p}, \cdots, \mathbf{a}^{n_p}_{br,p}], \tag{8}$$

where $\mathbf{a}^i_{br,p}$ is the receive spatial signature for i^{th} remote terminal assigned to channel p.

Channel selector 35 calculates functions of these signature matrices to assess whether or not communication between the base station and the new remote terminal can be successfully carried out on the selected conventional channel. In the preferred embodiment, channel selector 35 first calculates spatial multiplexing and demultiplexing weights for that remote terminal and then uses these weights to estimate link performance.

In the illustrative embodiment, spatial multiplexing weights are the rows of a matrix W_{tx} given in equation (9):

$$W_{tx} = S_b(A_{rb}A^*_{rb})^{-1}A_{rb}, \tag{9}$$

where $(\cdot)^{-1}$ is the inverse of a matrix, $(\cdot)^*$ is the complex conjugate transpose of a matrix, A_{rb} is the multiplexing spatial signature matrix $A_{rb,p}$ associated with the relevant conventional channel, and S_b is a (diagonal) matrix containing the amplitudes of the signals to be transmitted. The amplitudes to be transmitted, S_b, are calculated in the preferred embodiment using the (diagonal) matrix of remote terminal receiver mean-square noise voltages (N) and the diagonal matrix of minimum desired signal qualities (SNR_{des}) as given in equation (10):

$$S_b = (SNR_{des} \times N)^{1/2} \tag{10}$$

Now channel selector 35 calculates the average mean-square voltage (power) $\overline{P_b}$ to be transmitted from each element as the sum of squares of the elements in each row of W_{tx}, i.e.,

$$\overline{P_b} = \mathrm{diag}\{W_{tx}W^*_{tx}\}. \tag{11}$$

and the peak square voltage (power) P_b^{peak} to be transmitted from each element as the square of sum of the magnitude of the elements in each row of W_{tx}, *i.e.*,

$$P_b^{peak} = \mathrm{diag}\{abs(W_{tx})\,\mathbf{I}\,abs(W_{tx}^*)\}, \tag{12}$$

where $\mathbf{I}$ is a matrix of all ones of the appropriate size and $abs(\cdot)$ is elementwise absolute value. Channel selector 35 compares these values against the limits for each of the transmitters for each of the elements. If any of the average or peak values exceed the acceptable limits, the remote terminal in question is not assigned to the candidate channel. Otherwise, the ability to successfully receive from the remote terminal is checked. In an alternate embodiment, the transmitter limits are used as inequality constraints in an optimization algorithm for calculating transmit weights that meet the specifications given and that also result in the minimum amount of transmitted power possible. If transmit weights satisfying the constraints can not be found, the remote terminal in question is not assigned to the candidate channel. Such optimization algorithms are well known.

To test the uplink, channel selector 35 calculates spatial demultiplexing weights W_{rx} using A_{br}, the demultiplexing spatial signature matrix $A_{br,p}$ associated with the relevant conventional channel, as given for the preferred embodiment in equation (13):

$$W_{rx} = (A_{br}P_rA_{br}^* + R_{nn})^{-1}A_{br}P_r, \tag{13}$$

where P_r is a (diagonal) matrix of mean-square amplitudes (powers) transmitted by the remote terminals and R_{nn} is the base station receiver noise covariance. Then, the expected value of the normalized mean-squared error covariance is calculated in one embodiment as follows:

$$\overline{MSE} = P_r^{-1/2}((I - W_{rx}^*A_{br})P_r(I - W_{rx}^*A_{br})^* + W_{rx}^*R_{nn}W_{rx})P_r^{-*/2} \tag{14}$$

The notation $(\cdot)^{-*/2}$ indicates complex conjugate transpose of the square root of the matrix. The inverse of MSE is an estimate of the expected Signal-to-Interference-plus-Noise Ratio ($SINR$) at the output of the spatial demultiplexer:

$$\overline{SINR} = \overline{MSE}^{-1}. \tag{15}$$

If all of the diagonal elements of $\overline{SINR}$ are above the desired thresholds based on the signal quality required to be received from each remote terminal, the remote terminal is allowed access to the channel. If the candidate remote terminal is below its threshold and has the ability to increase its output power, the same computations are again performed for increasing remote terminal power output until either the maximum output power for that remote terminal is reached and the $\overline{SINR}$ is still insufficient, another remote terminal $\overline{SINR}$ falls below its threshold in which case its power is increased if possible, or all thresholds are exceeded. If acceptable remote terminal transmit powers can be found, the remote terminal is granted access to this particular conventional channel, otherwise it is denied access and another conventional channel is checked.

In an alternate embodiment, the calculation of demultiplexing weights is performed using well known optimization procedures with the objective of minimizing remote terminal transmit powers subject to estimated signals at the base station meeting or exceeding their minimum desired $SINR$'s.

Also, in an alternate embodiment, in the case that no conventional channel can be found to accommodate the remote terminal, channel selector 35 calculates whether some rearrangement of the existing remote terminals among the conventional channels would allow the remote terminal to be supported on

some conventional channel. In this case, the remote terminal will only be denied communication at this time if no rearrangement of existing users allows the remote terminal to be accommodated.

In an alternate embodiment employing frequency division duplexing (FDD), remote terminals are not restricted to being assigned a fixed conventional channel pair for transmit and receive. A sufficiently flexible system architecture is employed where channel selector 35 may choose to assign a particular remote to transmit and receive conventional channels separated by different frequency duplex offsets in order to minimize overall system interference levels.

Spatial multiplexing and demultiplexing weights for remote terminals already using a conventional channel must be recalculated because adding a new remote terminal to that conventional channel may change them significantly. In the preferred embodiment, channel selector 35, having already done the necessary calculations, sends the new spatial multiplexing and demultiplexing weights to the spatial weight processor 37 for use in setting up the spatial multiplexer 23 and demultiplexer 20. In an alternate embodiment, spatial weight processor 37 uses the spatial signature matrices sent to it by channel selector 35 to calculate different sets of spatial multiplexing and demultiplexing weights for all of the remote terminals on that conventional channel.

Spatial weight processor 37 then sends the new spatial demultiplexing weights to spatial demultiplexers 20 and the new spatial multiplexing weights to the spatial multiplexers 23 for this conventional channel, updates the active remote terminal list 34, and informs spatial processor controller 33 which in turn informs base station controller 3 of the selected channel. Base station controller 3 then transmits a message to the remote terminal using the downlink control channel that instructs the remote terminal to switch to the desired conventional channel.

It can be shown from equation (9) that the multiplexing weight matrices W_{tx} have the property:

$$A_{rb} W_{tx}^{*} = S_b. \tag{16}$$

This means that at the i^{th} remote terminal, the signal intended to be sent to that terminal is received with a sufficient (positive real) amplitude $S_b(i,i)$. The fact that S_b has zero off-diagonal elements means that at the i^{th} remote terminal, none of the other signals being transmitted are received by that remote terminal. In this manner, each remote terminal receives only the signals intended for it at the necessary power levels to ensure proper communications. In alternate embodiments, uncertainties in the estimates of A_{rb} are incorporated in setting base station transmit power levels and calculating weights so as to minimize the effect of errors and/or changes in A_{rb}.

Similarly, at the base station the particular demultiplexing weight matrices given in (13) have the property that conditioned on the knowledge of the receive spatial signatures and the transmitted voltages (powers) from the remote terminals, the estimated signals $\hat{S}$ given by:

$$\hat{S} = W_{rx}^{*} \mathbf{z}_b, \tag{17}$$

are the most accurate in the sense of least mean-squared error. In particular, they most closely match the signals transmitted by the remote terminals given the measurements made at the base station by the multiple antenna elements.

Equations (9) and (13) represent only one way to calculate spatial multiplexing and demultiplexing weights. There are other similar strategies that demonstrate properties similar to those shown in equation (16) and described in the previous paragraph. Other well known techniques for calculating weight matrices

W_{tx} and W_{rx} account for uncertainty in spatial signature matrices A_{rb} and A_{br}, for wide bandwidth conventional channels. and can incorporate more complex power and dynamic range constraints.

Determining Spatial Signatures

As shown in figure 6, spatial processor 13 also contains a spatial signature processor 38 for finding the spatial signatures of the remote terminals. In the illustrative embodiment, spatial signature processor 38 uses the calibration techniques described in copending U.S. patent application 08/234,747.

In the illustrative embodiment, each remote terminal is capable of entering a calibration mode in which the signal received by the remote terminal 43 is transmitted back to base station 1. Referring to figure 7, this function is provided by switch 63 controlled by remote terminal CPU 62 through switch control signal 64.

To determine the transmit and receive spatial signatures of a remote terminal, spatial signature processor 38 commands the remote terminal to enter calibration mode by transmitting a command to it on the downlink channel. This command is generated by base station controller 3, based on a request from spatial processor controller 33, and modulated by signal modulators 24. Spatial signature processor 38 then transmits predetermined calibration signals 11, on the conventional channel occupied by the remote terminal, by instructing multichannel transmitters 17(a, ..., m) via transmitter control data 31 and spatial processor controller 33. In the present embodiment, the m signals (for each antenna) among the predetermined calibration signals 11 are different frequency complex sinusoids. In another embodiment, the predetermined calibration signals 11 are any known, distinct, signals.

The remote terminal shown in figure 7 transmits back the signal received at the remote terminal. This transponded signal is received by multichannel receivers 15 in base station 1 shown in figure 1 and supplied to spatial signature processor 38 shown in figure 6. In one embodiment described in patent application 08/234,747, spatial signature processor 38 computes the receive and transmit spatial signatures of the remote terminal from the received signal measurements 6 and predetermined calibration signals 11 as follows. Time samples of the received data are stored in an m by n data matrix $\mathbf{Z}$ which in the absence of noise and parameter offsets is given by

$$\mathbf{Z} = k\mathbf{a}_{br}\mathbf{a}_{rb}\mathbf{S}, \tag{18}$$

where $\mathbf{S}$ is the m by n matrix of predetermined calibration signals and k is a known amount by which the signal is amplified in the remote terminal before transmission back to the base station. The receive spatial signature is proportional to the singular vector ($\mathbf{u}_1$) corresponding to the largest singular value (σ_{max} of the data matrix $\mathbf{Z}$. Transmission of a unit power signal from the remote terminal and received by the base station at antenna element 1 provides the necessary scaling g_{br} for the receive spatial signature

$$\mathbf{a}_{br} = g_{br}\mathbf{u}_1/\mathbf{u}_1(1), \tag{19}$$

where $\mathbf{u}_1(1)$ is the first element of $\mathbf{u}_1$. Once $\mathbf{a}_{br}$ is known, $\mathbf{a}_{rb}$ is calculated by

$$\mathbf{a}_{rb} = k^{-1}(g_{br}\mathbf{u}_1/\mathbf{u}_1(1))^{\dagger}\mathbf{Z}\mathbf{S}^{\dagger}, \tag{20}$$

where $B^{\dagger}$ is the well known Moore-Penrose pseudo-inverse of the matrix B satisfying $BB^{\dagger} = I$ (the identity matrix) for full-rank matrices B having more columns than rows. $B^{\dagger}B = I$ for full-rank matrices B having more rows than columns. In alternate embodiments also described in copending application 08/234,747,

well known techniques are used to account for noise present in the system and parameter variations such as oscillator frequency offsets.

Spatial signature processor 38 stores the new spatial signatures in remote terminal database 36. Upon completion, spatial signature processor 38 commands the remote terminal to exit calibration mode by transmitting a command to it on the downlink channel.

In one alternate embodiment, computation of remote terminal transmit spatial signatures can be performed directly by the remote terminals. This embodiment of the remote terminal is shown in figure 8. In calibration mode, spatial signature processor 38 transmits predetermined calibration signals 11, on the conventional channel to be calibrated by the remote terminals, as before. Remote terminal CPU 62 uses received calibration signals 44 and the known transmitted waveforms to compute the remote terminal's transmit spatial signature using the same techniques used by spatial signature processor 38 in the previous embodiment. The computed transmit spatial signature is transmitted back to base station 1 through modulator 51 and transmitter 54 as control data to be transmitted 52. When received by base station 1, spatial signature processor 38 stores the new transmit spatial signature in remote terminal database 36. Since each remote terminal performs the transmit spatial signature calculation independently, this arrangement allows multiple remote terminals to compute their own transmit spatial signature simultaneously on the same conventional channel. In this embodiment, remote terminal receive spatial signatures are computed by spatial signature processor 38 in the same manner as in the previous embodiment.

Using these techniques, spatial signature processor 38 can measure a remote terminal transmit and receive spatial signatures for a particular channel any time that channel is idle. The efficiency of these calibration techniques allow spatial signature processor 38 to update the spatial signatures of numerous remote terminals for a particular channel while occupying that channel for only a short time.

Many other techniques for obtaining spatial signatures of remote terminals are also available. In some RF environments, spatial signatures for remote terminals can be determined using well-known techniques that depend upon knowledge of the geometric arrangement of the m reception antennas 19(a.....m) and their individual directivity patterns (element gain and phase, with respect to a reference, as a function of angle-of-arrival), and the direction from the base station to the remote terminal. Furthermore, techniques such as ESPRIT (U.S. patents 4,750,147 and 4,965,732) can be used to estimate directions in applications where they are not known a priori.

Similarly, as is well known, knowledge of any predetermined modulation format parameters of the underlying signals being transmitted by the remote terminals (for example, knowledge of certain training or preamble sequences, or knowledge that the signals are constant modulus) can also be used to determine the receive spatial signatures for remote terminals. A further example is decision-directed feedback techniques, also well known in the art, where receive data is demodulated and then remodulated to produce an estimate of the original modulated signal. These techniques allow receive spatial signatures to be estimated even when multiple remote terminals are occupying a single conventional channel.

In some RF environments, transmit spatial signatures for remote terminals can be calculated explicitly, as is well known, using knowledge of the remote terminal locations and the locations and directivity patterns of the base station transmit antennas. This requires no special capability on the part of the remote terminal.

If the remote terminal has the ability to measure and report the strength of the signal it is receiving, the system can use this information to derive transmit spatial signatures, albeit in a less efficient manner than the embodiment shown in figure 7 where the remote terminal has full transponder capabilities, or the

embodiment shown in figure 8 where the remote terminal directly computes its transmit spatial signature. The transmit spatial signature is determined based solely on received signal power reports from the remote terminal as follows. First, spatial signature processor 38 transmits identical unit power signals from two of the m antenna elements at a time. Spatial signature processor 38 then changes the amplitude and phase of one of the two signals until the remote terminal reports that it is receiving no signal. The set of complex weights for antenna elements 2 through m required to null a unit power signal from element 1 are changed in sign and inverted to produce the transmit spatial signature for the remote terminal.

In yet another embodiment, the system can be designed to continuously update the spatial signatures of the remote terminals in a "closed loop" manner. This is done to account for the time variation of spatial signatures due to, for example, motion of the remote terminal or changes in the RF propagation conditions. To do this, both the base station and the remote terminal periodically transmit predetermined training sequences. Each remote terminal currently active on a particular channel is assigned a different predetermined training sequence and is given the training sequences for all other remotes currently active on that particular channel. In one embodiment, the different training sequences are orthogonal in the sense that the inner product of any two of the training sequence waveforms is zero. Each time the training sequences are transmitted, each remote terminal calculates how much of each training sequence it has received using well known techniques, and transmits this information to the base station.

In the illustrative embodiment, the base station uses the receiver outputs and knowledge of the transmitted waveforms to calculate the remote terminal receive spatial signatures. In another embodiment, the base station calculates how much of each remotely transmitted training sequence has come through on each output of the spatial demultiplexer, expressed as a complex vector of coupling coefficients. Knowledge of these coupling coefficients allows the currently active receive and transmit spatial signatures to be corrected so as to reduce mutual interference using well know techniques.

Finally, in systems that use time division duplexing (TDD) for full-duplex communications, as is well known in the art, the transmit and receive frequencies are the same. In this case, using the well known principle of reciprocity, the transmit and receive spatial signatures are directly related. Thus, this embodiment determines only one of the signatures, for example the receive spatial signature, and the other, in this case the transmit spatial signature, is calculated from the first (receive) spatial signature and knowledge of the relative phase and amplitude characteristics of multichannel receivers 15 and multichannel transmitters 14.

Network Level Spatial Processing

In the embodiment illustrated herein, the spatial processor for each base station in the cellular-like wireless communication system operates independently to maximize the number of communication channels in the immediate cell. However, significant system capacity improvements can be realized if the spatial processor from each base station communicates with and coordinates its efforts with the spatial processors from other nearby cells. A specific embodiment is shown in figure 9.

A multiple base station controller 66 acts as the interface between the wide area network 65 through link 68 and base stations 1 (a,b,c) via base station communication links 2 (a,b,c). Each base station is responsible for providing coverage to a number of remote terminals. In one embodiment, each remote terminal is assigned to only one base station thus defining cell boundaries 67 (a,b,c) within which all

remotes attached to a particular base station are located. Users equipped with remote terminals 69 are identified by a boxed "R" in the figure.

Each spatial processor contained in base stations 1 (a,b,c) measures and stores the spatial signatures of the remote terminals in its cell and also of the remote terminals in adjacent cells. The determination of spatial signatures of the remote terminals in adjacent cells is coordinated by multiple base station controller 66 through base station communication links 2 (a,b,c). Through base station communication links 2 (a,b,c) and multiple base station controller 66, spatial processors in base stations 1 (a,b,c) from adjacent cells inform each other of which remote terminals they are communicating with on which conventional channels. Each spatial processor includes the spatial signatures of remote terminals that are currently active in adjacent cells to form extended transmit and receive spatial signature matrices A_{rb} and A_{br} which are sent to all the adjacent base stations. The channel selectors in each base station, using these extended spatial signature matrices, jointly assign remote terminals to each conventional channel in each of base stations 1 (a,b,c).

The resultant weight matrices W_{tr} and W_{rr} for each base station are then calculated using extended spatial signature matrices A_{rb} and A_{br}. In calculating the weights, the objective is to minimize the signal transmitted to and received from the adjacent cell's active remote terminals, thereby allowing many more remote terminals to simultaneously communicate.

In an alternate embodiment, multiple base station controller 66 assigns remote terminals requesting access to base stations dynamically using a list of active remote terminal/base station/conventional channel links, the associated remote terminal databases, and the particular requirements for the link to be assigned. Additionally, remote terminals can employ multiple (directional) transmit and receive antennas, to facilitate directive links to multiple nearby base stations as instructed by multiple base station controller 66 to further increase system capacity.

Advantages

The apparatus and method in accordance with the invention provides a significant advantage over the prior art in that it allows many remote terminals to simultaneously share the same conventional communication channel. In particular, for a system with m receive and m transmit antenna elements, up to m remote terminals can share a single conventional communication channel. Moreover, signals received from and transmitted to the remote terminals have substantially improved signal-to-noise, reduced interference, and improved quality in multipath environments compared to a standard base station.

Thus, a wireless communication system can support many times more conversations, or have a much greater data throughput, with the same amount of spectrum. Alternatively, a wireless communication system can support the same number of conversations or data throughput with much less spectrum.

Alternate Embodiments

In one alternate embodiment, transmission antennas 18(a,...,m) and reception antennas 19(a,...,m) at base station 1 are replaced by a single array of m antennas. Each element in this array is attached to both its respective component of multichannel transmitters 14 and its respective component of multichannel receivers 15 by means of a duplexer.

In another alternate embodiment, signals on the uplink control channel may be processed in real time using the spatial processing described in copending patent application 07/806.695. This would allow multiple remote terminals to request a communication channel at the same time.

In yet another embodiment for applications involving data transfer of short bursts or packets of data, no separate uplink control channel is required and the system may service requests for communication and other control functions during control time intervals that are interspersed with communications intervals.

As stated above, many techniques are known for measuring the spatial signatures of the remote terminal radios and using these spatial signatures to calculate multiplexing and demultiplexing weights that will allow multiple simultaneous conversations and/or data transfers on the same conventional communication channel.

While the above description contains many specificities, these should not be construed as limitations on the scope of the invention, but rather as an exemplification of one preferred embodiment thereof. Many other variations are possible. Accordingly, the scope of the invention should be determined not by the illustrated embodiments, but by the appended claims and their legal equivalents.

What is claimed is:

1. A wireless system at a base station for receiving uplink signals transmitted from a plurality of remote terminals using a common conventional uplink channel comprising:

    receiving means including a plurality of antenna elements and receivers for producing measurements of combinations of said uplink signals,

    receive spatial processing means for determining and storing receive spatial signatures for said plurality of remote terminals using said measurements, and

    spatial demultiplexing means using said receive spatial signatures and said measurements to produce separated uplink signals,

    whereby said uplink signals from said plurality of remote terminals can be received independently while simultaneously communicating on said common conventional uplink channel.

2. The wireless system as defined by claim 1 wherein said receive spatial processing means comprises:

    a receive spatial signature list comprising a receive spatial signature for each of said remote terminals and said common conventional uplink channel,

    receive spatial signature determining means for determining said receive spatial signatures,

    a receive channel selector utilizing said receive spatial signatures to determine whether said common conventional uplink channel can be further shared by an additional remote terminal, and

    a receive spatial weight processor for calculating spatial demultiplexing weights for said plurality of remote terminals, said spatial demultiplexing weights being utilized by said spatial demultiplexing means to produce said separated uplink signals.

3. The wireless system as defined by claim 2 wherein said receive spatial weight processor determines said spatial demultiplexing weights as the columns of matrix W_{rx} as follows:

$$W_{rx} = (A_{br} P_r A_{br}^* + R_{nn})^{-1} A_{br} P_r,$$

    where $()^*$ denotes the complex conjugate transpose of a matrix, R_{nn} is a base station receiver noise covariance matrix, P_r is a diagonal matrix of remote terminal transmit powers, and A_{br} is a demultiplexing spatial signature matrix whose columns are said receive spatial signatures for said plurality of remote terminals and said common conventional uplink channel.

4. The wireless system as defined by claim 1 wherein said common conventional uplink channel is one of a plurality of conventional uplink channels and wherein said receive spatial processing means comprises:

    a receive active remote terminal list of remote terminals assigned to each of said conventional uplink channels,

    a receive spatial signature list comprising a receive spatial signature for each of said remote terminals and each of said conventional uplink channels,

receive spatial signature determining means for determining said receive spatial signatures,

a receive channel selector using said receive active remote terminal list and said receive spatial signature list to determine assignments of said remote terminals to said conventional uplink channels, and

a receive spatial weight processor for calculating spatial demultiplexing weights for each of said remote terminals assigned to each of said conventional uplink channels said spatial demultiplexing weights being utilized by said spatial demultiplexing means to produce said separated uplink signals.

5. The wireless system as defined by claim 4 wherein said base station is one of a plurality of base stations and said channel selector at each of said base stations further comprises:

communication means for communicating with said channel selector at each of said base stations, and

joint channel selector means for jointly determining assignments of said remote terminals to said conventional uplink channels and said base stations.

whereby said uplink signals from a maximum number of said remote terminals can be received independently by at least one of said base stations while simultaneously communicating on said common conventional uplink channels.

6. The wireless system as defined by claim 1 and including transmission means comprising a transmitter and an omnidirectional antenna for sending downlink signals from said base station to said plurality of remote terminals.

7. The wireless system as defined by claim 1 wherein said spatial demultiplexing means calculates spatial demultiplexing weights for said common conventional uplink channel as the columns of a matrix W_{rx} as follows:

$$W_{rx} = (A_{br}P_rA_{br}^* + R_{nn})^{-1}A_{br}P_r.$$

where $(\cdot)^*$ denotes the complex conjugate transpose of a matrix, $(\cdot)^{-1}$ denotes the inverse of a matrix, R_{nn} is a base station receiver noise covariance matrix. P_r is a diagonal matrix of remote terminal transmit powers, and A_{br} is a demultiplexing spatial signature matrix whose columns are said receive spatial signatures for said plurality of remote terminals and said common conventional uplink channel, said spatial demultiplexing means using said spatial demultiplexing weights to produce said separated uplink signals.

8. The wireless system as defined by claim 1 wherein said receive spatial processing means determines said receive spatial signatures using signals transponded from transponders co-located with each of said plurality of remote terminals.

9. The wireless system as defined by claim 1 wherein said receive spatial processing means determines said receive spatial signatures using location and directivity knowledge of said antenna elements, and the directions of arrival of said uplink signals from said plurality of remote terminals.

10. The wireless system as defined by claim 1 wherein said receive spatial processing means determines said receive spatial signatures using location and directivity knowledge of said antenna elements and location knowledge of said plurality of remote terminals.

11. The wireless system as defined by claim 1 wherein said receive spatial processing means determines said receive spatial signatures using predetermined modulation format parameters of said uplink signals from said plurality of remote terminals.

12. The wireless system as defined by claim 1 further comprising:

    transmission means including a plurality of transmit antenna elements and transmitters for transmitting multiplexed downlink signals to said plurality of remote terminals using a common conventional downlink channel,

    transmit spatial processing means for determining and storing transmit spatial signatures for said plurality of remote terminals, and

    spatial multiplexing means using said transmit spatial signatures and downlink signals to produce said multiplexed downlink signals,

whereby said base station can transmit said downlink signals to said plurality of remote terminals independently and simultaneously on said common conventional downlink channel.

13. The wireless system as defined by claim 12 wherein said receiving means and said transmission means share common antenna elements using duplexers.

14. The wireless system as defined by claim 12 wherein said receiving means and said transmission means share common antenna elements using transmit/receive switches.

15. The wireless system as defined by claim 12 wherein said common conventional uplink channel is one of a plurality of conventional uplink channels, said common conventional downlink channel is one of a plurality of conventional downlink channels. and wherein said receive spatial processing means and said transmit spatial processing means comprises:

    an active remote terminal list of remote terminals assigned to each of said conventional uplink channels and each of said conventional downlink channels,

    a spatial signature list comprising a receive spatial signature for each of said remote terminals and each of said conventional uplink channels, and a transmit spatial signature for each of said remote terminals and each of said conventional downlink channels,

    receive spatial signature determining means for determining said receive spatial signatures,

    transmit spatial signature determining means for determining said transmit spatial signatures,

    a channel selector using said active remote terminal list and said receive spatial signature list and said transmit spatial signature list to determine assignments of said remote terminals to said conventional uplink channels and said conventional downlink channels,

a receive spatial weight processor for calculating spatial demultiplexing weights for each of said remote terminals assigned to each of said conventional uplink channels, said spatial demultiplexing weights being utilized by said spatial demultiplexing means to produce said separated uplink signals, and

a transmit spatial weight processor for calculating spatial multiplexing weights for each of said remote terminals assigned to each of said conventional downlink channels, said spatial multiplexing weights being utilized by said spatial multiplexing means to produce said multiplexed downlink signals.

16. The wireless system as defined by claim 15 wherein said base station is one of a plurality of base stations and said channel selector at each of said base stations further comprises:

communication means for communicating with said channel selector at each of said base stations, and

joint channel selector means for jointly determining assignments for said remote terminals to said conventional uplink channels and said conventional downlink channels and said base stations,

whereby said uplink signals from a maximum number of said remote terminals can be received independently by at least one of said base stations and said downlink signals can be transmitted independently to a maximum number of said remote terminals by at least one of said base stations, while simultaneously communicating on said common conventional uplink channels and said common conventional downlink channels.

17. The wireless system as defined by claim 12 wherein said spatial multiplexing means determines spatial multiplexing weights for said common conventional downlink channel as the rows of a matrix W_{tr} as follows:

$$W_{tr} = S_b(A_{rb}A_{rb}^*)^{-1}A_{rb},$$

where $(\cdot)^*$ denotes the complex conjugate transpose of a matrix, $(\cdot)^{-1}$ denotes the inverse of a matrix, S_b is a diagonal matrix of amplitudes of said downlink signals, and A_{rb} is a multiplexing spatial signature matrix whose rows are said transmit spatial signatures for said plurality of remote terminals and said common conventional downlink channel and said spatial multiplexing means utilizes said spatial multiplexing weights to produce said multiplexed downlink signals.

18. The wireless system as defined by claim 12 wherein said transmit spatial processing means determines said transmit spatial signatures using signals transponded from transponders co-located with said plurality of remote terminals.

19. The wireless system as defined by claim 12 wherein said transmit spatial processing means determines said transmit spatial signatures using signals transponded by said plurality of remote terminals.

20. The wireless system as defined by claim 12 wherein said transmit spatial signatures are determined by said plurality of remote terminals using predetermined modulation format parameters of said downlink signals.

21. The wireless system as defined by claim 12 wherein said transmit spatial processing means determines said transmit spatial signatures using knowledge of locations and directivity of said transmit antenna elements and estimates of directions of arrival of said uplink signals from said plurality of remote terminals.

22. The wireless system as defined by claim 12 wherein said downlink signals and said uplink signals are transmitted on the same radio frequency and said transmit spatial processing means determines said transmit spatial signatures by calculating them directly from said receive spatial signatures.

23. The wireless system as defined by claim 12 wherein said transmit spatial processing means determines said transmit spatial signatures using location and directivity knowledge of said antenna elements and location knowledge of said plurality of remote terminals.

24. A wireless system at a base station for transmitting to a plurality of remote terminals using a common conventional downlink channel comprising:

transmission means including a plurality of transmit antenna elements and transmitters for transmitting multiplexed downlink signals to said plurality of remote terminals,

transmit spatial processing means for determining and storing transmit spatial signatures for said plurality of remote terminals, and

spatial multiplexing means using said transmit spatial signatures and downlink signals to produce said multiplexed downlink signals,

whereby said base station can transmit said downlink signals to said plurality of remote terminals independently and simultaneously on a common conventional downlink channel.

25. The wireless system as defined by claim 24 wherein said common conventional downlink channel is one of a plurality of conventional downlink channels and wherein said transmit spatial processing means comprises:

a transmit active remote terminal list of remote terminals assigned to each of said conventional downlink channels,

a transmit spatial signature list comprising a transmit spatial signature for each of said remote terminals and each of said conventional downlink channels.

transmit spatial signature determining means for determining said transmit spatial signatures,

a transmit channel selector using said transmit active remote terminal list and said transmit spatial signature list to determine assignments of said remote terminals to said conventional downlink channels, and

a transmit spatial weight processor for calculating spatial multiplexing weights for each of said remote terminals assigned to each of said conventional downlink channels said spatial multiplexing weights being utilized by said spatial multiplexing means to produce said multiplexed downlink signals.

26. The wireless system as defined by claim 25 wherein said base station is one of a plurality of base stations and said transmit channel selector at each of said base stations further comprises:

communication means for communicating with said transmit channel selector at each of said base stations, and

joint channel selector means for jointly determining assignments of said remote terminals to said conventional downlink channels and said base stations,

whereby said downlink signals can be transmitted independently to a maximum number of said remote terminals by at least one of said base stations, while simultaneously communicating on said common conventional downlink channels.

27. The wireless system as defined by claim 24 wherein said spatial multiplexing means determines spatial multiplexing weights for said common conventional downlink channel as the rows of a matrix W_{tx} as follows:

$$W_{tx} = S_b(A_{rb}A_{rb}^*)^{-1}A_{rb},$$

where $(\cdot)^*$ denotes the complex conjugate transpose of a matrix, $(\cdot)^{-1}$ denotes the inverse of a matrix, S_b is a diagonal matrix of amplitudes of said downlink signals, and A_{rb} is a multiplexing spatial signature matrix whose rows are said transmit spatial signatures for said plurality of remote terminals and said common conventional downlink channel and said spatial multiplexing means utilizes said spatial multiplexing weights to produce said multiplexed downlink signals.

28. The wireless system as defined by claim 24 wherein said transmit spatial processing means determines said transmit spatial signatures using signals transponded from transponders co-located with said plurality of remote terminals.

29. The wireless system as defined by claim 24 wherein said transmit spatial processing means determines said transmit spatial signatures using signals transponded by said plurality of remote terminals.

30. The wireless system as defined by claim 24 wherein said transmit spatial signatures are determined by said plurality of remote terminals using predetermined modulation format parameters of said downlink signals.

31. The wireless system as defined by claim 24 wherein said transmit spatial processing means determines said transmit spatial signatures using location and directivity knowledge of said antenna elements and location knowledge of said plurality of remote terminals.

AMENDED CLAIMS

[received by the International Bureau on 23 April 1996 (23.04.96); original claims 1-31 replaced by amended claims 1-35 (12 pages)]

1. A wireless system for calculating uplink signals transmitted from a plurality of remote terminals using a common uplink channel, said system including at least one base station, said system comprising:

receiving means at said at least one base station including a plurality of antenna elements and receivers for producing measurements of combinations of said uplink signals from said plurality of remote terminals using said common uplink channel,

receive spatial processing means for determining and storing receive spatial signatures for said plurality of remote terminals using said measurements, and

spatial demultiplexing means using said receive spatial signatures and said measurements to calculate said uplink signals.

2. The wireless system as defined by claim 1 wherein said receive spatial processing means comprises:

a spatial signature list comprising a receive spatial signature for each remote terminal in said plurality of remote terminals and said common uplink channel,

receive spatial signature determining means for determining said receive spatial signatures, and

a receive channel selector utilizing said receive spatial signatures to determine whether said common uplink channel can be further shared by an additional remote terminal.

3. The wireless system as defined by claim 2 wherein said receive spatial processing means further comprises:

a receive spatial weight processor for calculating spatial demultiplexing weights for said plurality of remote terminals, said spatial demultiplexing weights being utilized by said spatial demultiplexing means to calculate said uplink signals.

4. The wireless system as defined by claim 3 wherein said receive spatial weight processor determines said spatial demultiplexing weights as the columns of matrix W_{rx} as follows:

$$W_{rx} = (A_{br}P_rA^*_{br} + R_{nn})^{-1} A_{br}P_r$$

where ()* denotes the complex conjugate transpose of a matrix, R_{nn} is the noise covariance matrix of said receiving means, P_r is the diagonal matrix of transmit powers of the remote terminals in said plurality of remote terminals, and A_{br} is a demultiplexing spatial signature matrix whose columns are said receive spatial signatures for said plurality of remote terminals and said common uplink channel.

5. The wireless system as defined by claim 1 wherein said common uplink channel is one of a plurality of uplink channels and wherein said receive spatial processing means comprises:

an active remote terminal list comprising a list of remote terminals assigned to at least one channel of said plurality of uplink channels,

a spatial signature list comprising a receive spatial signature for each remote terminal of said plurality of remote terminals and each channel of said plurality of uplink channels,

receive spatial signature determining means for determining said receive spatial signatures in said spatial signature list,

a receive channel selector using said active remote terminal list and said spatial signature list to determine assignments of each remote terminal in said active remote terminal list to at least one of the channels of said plurality of uplink channels, and

a receive spatial weight processor for calculating spatial demultiplexing weights for each of the terminals in said active remote terminal list and each channel of said plurality of uplink channels assigned to at least one of the terminals in said active remote terminal list, said spatial demultiplexing weights being utilized by said spatial demultiplexing means to calculate said uplink signals.

6. The wireless system as defined by claim 1 wherein said common uplink channel is one of a plurality of uplink channels, said at least one base station is one of a plurality of base stations, said receive spatial processing means is one of a plurality of receive spatial processing means, each base station in said plurality of base stations having a corresponding receive spatial processing means in said plurality of receive spatial processing means, each receive spatial processing means in said plurality of receive spatial processing means comprising:

an active remote terminal list comprising a list of remote terminals assigned to at least one channel of said plurality of uplink channels,

a spatial signature list comprising a receive spatial signature for each remote terminal of said plurality of remote terminals and each channel of said plurality of uplink channels,

receive spatial signature determining means for determining said receive spatial signatures in said spatial signature list, and

a receive spatial weight processor for calculating spatial demultiplexing weights for each of the terminals in said active remote terminal list and each channel of said plurality of uplink channels assigned to at least one of the terminals in said active remote terminal list, said spatial demultiplexing weights being utilized by said spatial demultiplexing means to calculate said uplink signals,

said system further comprising:

joint channel selector means for jointly determining assignments of each remote terminal in each said active remote terminal list to at least one of the channels of said plurality of uplink channels and to at least one of base stations of said plurality of base stations, and

communication means for communicating the status of said assignments between each base station in said plurality of base stations and said joint channel selector means.

7. The wireless system as defined by claim 1 and including transmission means comprising a transmitter and an antenna for sending downlink signals from said at least one

base station to the terminals in said plurality of remote terminals.

8. The wireless system as defined by claim 1 wherein said spatial demultiplexing means calculates spatial demultiplexing weights for said common uplink channel as the columns of a matrix W_{rx} as follows:

$$W_{rx} = (A_{br}P_rA^*_{br} + R_{nn})^{-1} A_{br}P_r$$

where ()* denotes the complex conjugate transpose of a matrix, R_{nn} is the noise covariance matrix of said receiver means, P_r is the diagonal matrix of transmit powers of the remote terminals in said plurality of remote terminals, and A_{br} is a demultiplexing spatial signature matrix whose columns are said receive spatial signatures for said plurality of remote terminals and said common uplink channel, said spatial demultiplexing means using said spatial demultiplexing weights to calculate said uplink signals.

9. The wireless system as defined by claim 1 wherein said system includes a transponder co-located with each remote terminal of said plurality of remote terminals and wherein receive spatial processing means determines said receive spatial signatures using signals transponded from at least one of the transponders.

10. The wireless system as defined by claim 1 wherein each remote terminal of said plurality of remote terminals includes a transponder and said receive spatial processing means determines said receive spatial signatures using signals transponded from at least one of the transponders.

11. The wireless system as defined by claim 1 wherein said receive spatial processing means determines said receive spatial signatures using the known location and directivity of said antenna elements, and estimates of the directions of arrival of said uplink signals from said plurality of remote terminals.

12. The wireless system as defined by claim 1 wherein said receive spatial processing means determines said receive spatial signatures using the known location and directivity of said antenna elements and the known location of said plurality of remote terminals.

13. The wireless system as defined by claim 1 wherein said uplink signals have predetermined modulation format parameters, and said receive spatial processing means determines said receive spatial signatures using said predetermined modulation format parameters of said uplink signals from said plurality of remote terminals.

14. The wireless system as defined by claim 1 further comprising:

transmission means including a plurality of transmit antenna elements and transmitters for transmitting multiplexed downlink signals to said plurality of remote terminals using a common downlink channel,

transmit spatial processing means for determining and storing transmit spatial signatures for said plurality of remote terminals, and

spatial multiplexing means using said transmit spatial signatures and downlink signals to produce said multiplexed downlink signals.

15. The wireless system as defined by claim 14 wherein said receiving means and said transmission means share common antenna elements using duplexers.

16. The wireless system as defined by claim 14 wherein said receiving means and said transmission means share common antenna elements using transmit/receive switches.

17. The wireless system as defined by claim 14 wherein said common uplink channel is one of a plurality of uplink channels, said common downlink channel is one of a plurality of downlink channels, and wherein said receive spatial processing means and said transmit spatial processing means comprise:

an active remote terminal list comprising a list of remote terminals assigned to at least one of the channels of said plurality of uplink channels and remote terminals assigned to at least one of the channels of said plurality of downlink channels, a spatial signature list comprising a receive spatial signature for each remote terminal of said plurality of remote terminals and each channel of said plurality of uplink channels, and a transmit spatial signature for each remote terminal of said plurality of remote terminals and each channel of said plurality of downlink channels,

receive spatial signature determining means for determining said receive spatial signatures,

transmit spatial signature determining means for determining said transmit spatial signatures, and

a channel selector using said active remote terminal list and said spatial signature list to determine assignments of each remote terminal in said active remote terminal list to at least one of the channels of said plurality of uplink channels and at least one of the channels of said plurality of downlink channels.

18. The wireless system as defined by claim 17 wherein said receive spatial processing means and said transmit spatial processing means further comprise:

a receive spatial weight processor for calculating spatial demultiplexing weights for each of the terminals in said active remote terminals list to which a uplink channel is assigned and for each channel of said plurality of uplink channels assigned to at least one of the terminals in said active remote terminal list, said spatial demultiplexing weights being utilized by said spatial demultiplexing means to calculate said uplink signals, and

a transmit spatial weight processor for calculating spatial multiplexing weights for each of the terminals in said active remote terminal list to which a downlink channel is assigned and each channel of said plurality of downlink channels assigned to at least one of the terminals in said active remote terminal list, said spatial multiplexing weights being utilized by said spatial multiplexing means to produce said multiplexed downlink signals.

19. The wireless system as defined by claim 14 wherein said at least one base station is one of a plurality of base stations, said common uplink channel is one of a plurality of uplink channels, said common downlink channel is one of a plurality of downlink channels, said receive spatial processing means is one of a plurality of receive spatial processing means, said transmit spatial processing means is one of a plurality of transmit spatial processing means, each base station in said plurality of base stations having a corresponding receive spatial processing means in said plurality of receive spatial processing means and a corresponding transmit spatial processing means in said plurality of transmit spatial processing means, each receive spatial processing means in said plurality of receive spatial processing means and each transmit spatial processing means in said plurality of transmit spatial processing means comprising:

an active remote terminal list comprising a list of remote terminals assigned to at least one of the channels of said plurality of uplink channels and remote terminals assigned to at least one of the channels of said plurality of downlink channels, a spatial signature list comprising a receive spatial signature for each remote terminal of said plurality of remote terminals and each channel of said plurality of uplink channels, and a transmit spatial signature for each remote terminal of said plurality of remote terminals and each channel of said plurality of downlink channels,

receive spatial signature determining means for determining said receive spatial signatures,

transmit spatial signature determining means for determining said transmit spatial signatures,

a receive spatial weight processor for calculating spatial demultiplexing weights for each of the terminals in said active remote terminal list to which a uplink channel is assigned and each channel of said plurality of uplink channels assigned to at least one of the terminals in said active remote terminal list, said spatial demultiplexing weights being utilized by said spatial demultiplexing means to calculate said uplink signals, and

a transmit spatial weight processor for calculating spatial multiplexing weights for each of the terminals in said active remote terminal list to which a downlink channel is assigned and each channel of said plurality of downlink channels assigned to at least one of the terminals in said active remote terminal list, said spatial multiplexing weights being utilized by said spatial multiplexing means to produce said multiplexed downlink signals,

said system further comprising:

joint channel selector means for jointly determining assignments of each remote terminal in each said active remote terminal list to at least one of the channels of said plurality of uplink channels, to at least one of the channels of said plurality of downlink channels and to at least one of the base stations of said plurality of base stations, and

communication means for communicating said assignments between each base station in said plurality of base stations and said joint channel selector means.

20. The wireless system as defined by claim 14 wherein said spatial multiplexing means determines spatial multiplexing weights for said common downlink channel as the rows of a matrix W_{tx} as follows:

$$W_{tx} = S_b \ (A_{rb} A^*_{rb})^{-1} \ A_{rb},$$

where $()^*$ denotes the complex conjugate transpose of a matrix, S_b is the diagonal matrix of amplitudes of said downlink signals, and A_{rb} is a multiplexing spatial signature matrix whose rows are said transmit spatial signatures for said plurality of remote terminals and said common downlink channel, and wherein said spatial multiplexing means utilizes said spatial multiplexing weights to produce said multiplexed downlink signals.

21. The wireless system as defined by claim 14 wherein said system includes a transponder co-located with each remote terminal of said plurality of remote terminals and wherein transmit spatial processing means determines said transmit spatial signatures using signals transponded from at least one of the transponders.

22. The wireless system as defined by claim 14 wherein each remote terminal in said plurality of remote terminals includes a transponder, and wherein said transmit spatial processing means determines said transmit spatial signatures using signals transponded from at least one of the transponders.

23. The wireless system as defined by claim 14 wherein said downlink signals have predetermined modulation format parameters, and said transmit spatial signatures are determined by the corresponding terminals in said plurality of remote terminals using the predetermined modulation format parameters of said downlink signals.

24. The wireless system as defined by claim 14 wherein said transmit spatial processing means determines said transmit spatial signatures using the known location and directivity of said transmit antenna elements and estimates of directions of arrival of said uplink signals from said plurality of remote terminals.

25. The wireless system as defined by claim 14 wherein said downlink signals and said uplink signals are transmitted on the same radio frequency and said transmit spatial processing means determines said transmit spatial signatures by calculating them directly from said receive spatial signatures.

26. The wireless system as defined by claim 14 wherein said transmit spatial processing means determines said transmit spatial signatures using the known location and directivity of said antenna elements and the known location of said plurality of remote terminals.

27. A wireless system including at least one base station for transmitting to a plurality of remote terminals using a common downlink channel, said system comprising:

transmission means at said at least one base station including a plurality of transmit antenna elements and

transmitters for transmitting multiplexed downlink signals to said plurality of remote terminals,

transmit spatial processing means for determining transmit spatial signatures for said plurality of remote terminals, and

spatial multiplexing means using said transmit spatial signatures and downlink signals to produce said multiplexed downlink signals,

whereby said at least one base station can transmit said downlink signals to said plurality of remote terminals simultaneously on a common downlink channel.

28. The wireless system as defined by claim 27 wherein said common downlink channel is one of a plurality of downlink channels and wherein said transmit spatial processing means comprises:

an active remote terminal list comprising a list of remote terminals assigned to at least one the channels of said plurality of downlink channels,

a spatial signature list comprising a transmit spatial signature for each remote terminal of said plurality of remote terminals and each channel of said plurality of downlink channels,

transmit spatial signature determining means for determining said transmit spatial signatures, and

a transmit channel selector using said active remote terminal list and said spatial signature list to determine assignments of each remote terminal in said active remote terminal list to at least one of the channels of said plurality of downlink channels.

29. The wireless system as defined by claim 28 wherein said transmit spatial processing means further comprises:

a transmit spatial weight processor for calculating spatial multiplexing weights for each of the terminals in said active remote terminal list to which a downlink channel is assigned and each channel of said plurality of downlink channels assigned to at least one of the terminals in said active remote terminal list, said spatial multiplexing weights

being utilized by said spatial multiplexing means to produce said multiplexed downlink signals.

30. The wireless system as defined by claim 27 wherein said at least one base station is one of a plurality of base stations, said common downlink channel is one of a plurality of downlink channels, said transmit spatial processing means is one of a plurality of transmit spatial processing means, each base station in said plurality of base stations having a corresponding transmit spatial processing means in said plurality of transmit spatial processing means, each transmit spatial processing means in said plurality of transmit spatial processing means comprising:

an active remote terminal list comprising a list of remote terminals assigned to at least one the channels of said plurality of downlink channels,

a spatial signature list comprising a transmit spatial signature for each remote terminal of said plurality of remote terminals and each channel of said plurality of downlink channels,

transmit spatial signature determining means for determining said transmit spatial signatures, and

a transmit spatial weight processor for calculating spatial multiplexing weights for each of the terminals in said active remote terminal list to which a downlink channel is assigned and each channel of said plurality of downlink channels assigned to at least one of the terminals in said active remote terminal list, said spatial multiplexing weights being utilized by said spatial multiplexing means to produce said multiplexed downlink signals,

said system further comprising:

joint channel selector means for jointly determining assignments of each remote terminal in each said active remote terminal list to at least one of the channels of said plurality of down channels and to at least one of the base stations of said plurality of base stations, and

communication means for communicating said assignments between each base station in said plurality of base stations and said joint channel selector means.

31. The wireless system as defined by claim 27 wherein said spatial multiplexing means determines spatial multiplexing weights for said common downlink channel as the rows of a matrix W_{tx} as follows:

$$W_{tx} = S_b \ (A_{rb}A^*_{rb})^{-1}A_{rb}$$

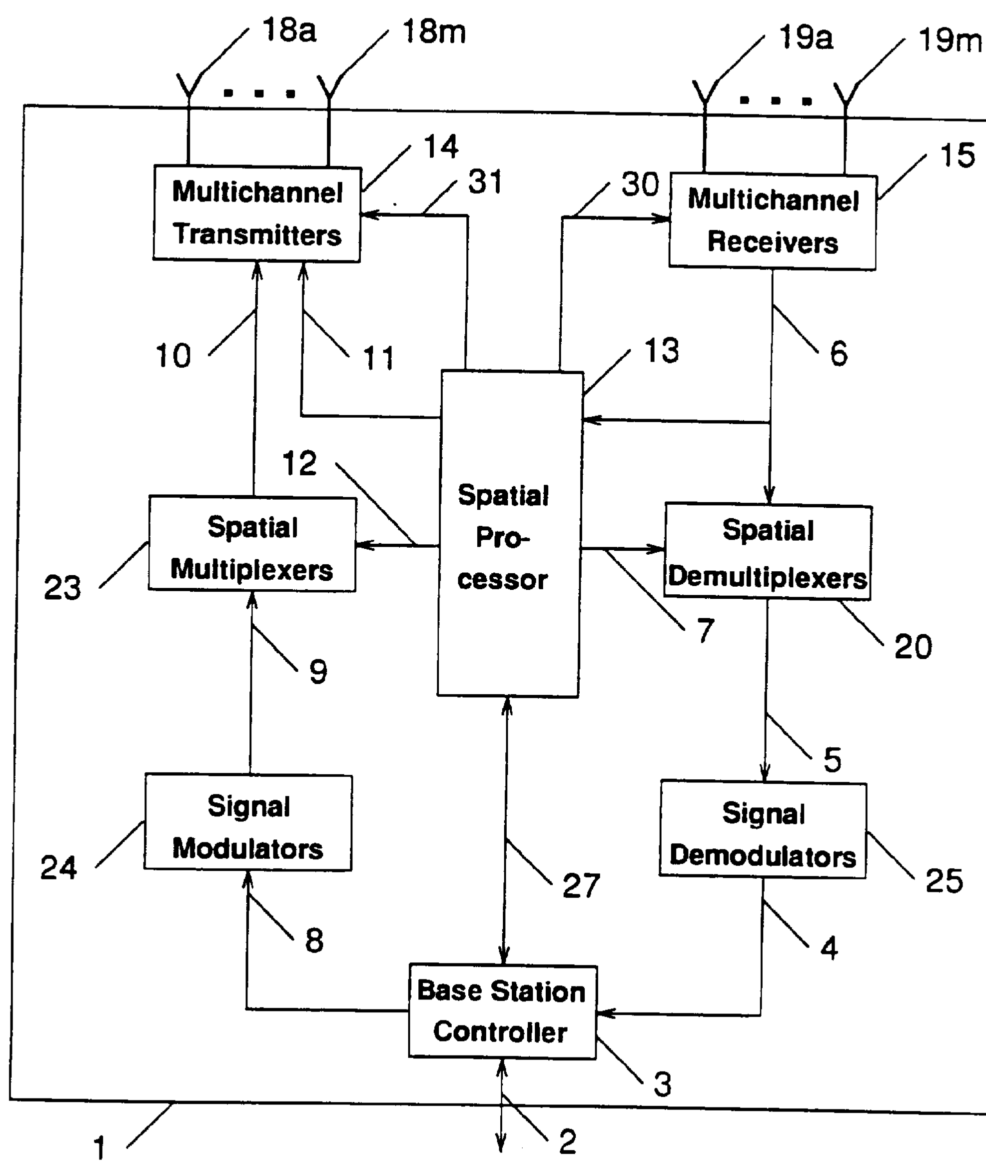
where $()^*$ denotes the complex conjugate transpose of a matrix, S_b is the diagonal matrix of amplitudes of said downlink signals, and A_{rb} is a multiplexing spatial signature matrix whose rows are said transmit spatial signatures for said plurality of remote terminals and said common downlink channel, and said spatial multiplexing means utilizes said spatial multiplexing weights to produce said multiplexed downlink signals.

32. The wireless system as defined by claim 27 wherein said system includes a transponder co-located with each remote terminal of said plurality of remote terminals and wherein said transmit spatial processing means determines said transmit spatial signatures using signals transponded from at least one of the transponders.

33. The wireless system as defined by claim 27 wherein each remote terminal in said plurality of remote terminals includes a transponder, and wherein said transmit spatial processing means determines said transmit spatial signatures using signals transponded from at least one of the transponders.

34. The wireless system as defined by claim 27 wherein said downlink signals have predetermined modulation format parameters, and said transmit spatial signatures are determined by the corresponding terminals in said plurality of remote terminals using the predetermined modulation format parameters of said downlink signals.

35. The wireless system as defined by claim 27 wherein said transmit spatial processing means determines said transmit spatial signatures using the known location and directivity of said antenna elements and the known location of said plurality of remote terminals.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18m
19a
19m
Multichannel Transmitters
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31
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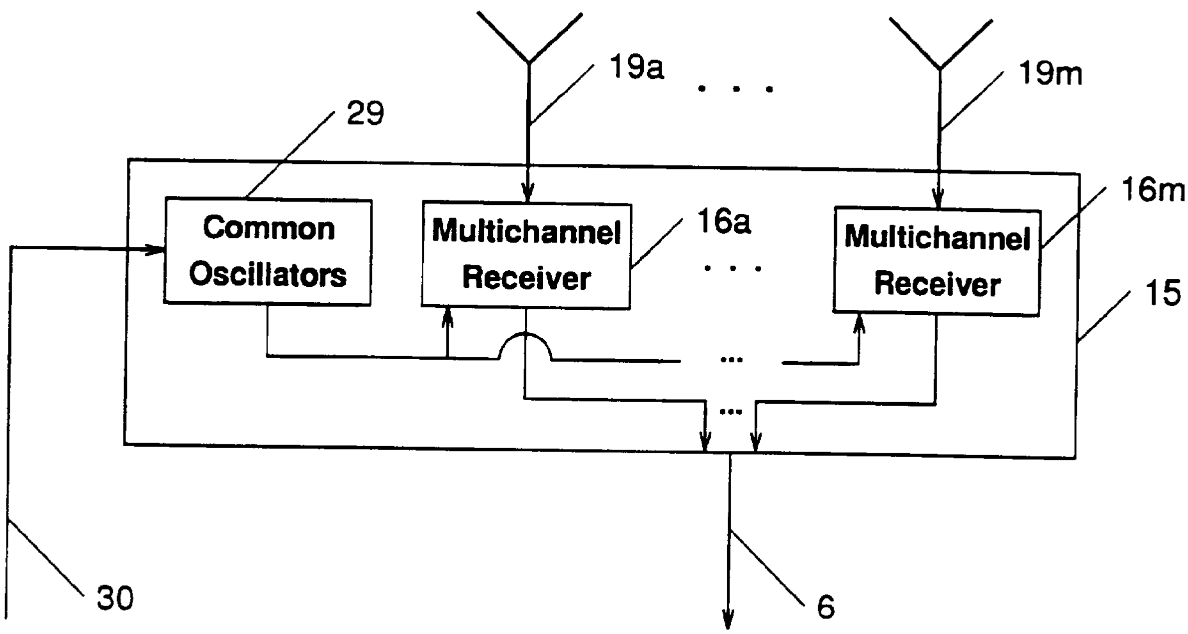
Multichannel Receivers
15
10
11
13
6
12
Spatial Multiplexers
Spatial Pro-cessor
Spatial Demultiplexers
23
7
20
9
5
Signal Modulators
Signal Demodulators
24
27
25
8
4
Base Station Controller
3
1
2

FIG. 1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19m
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16m
Common Oscillators
Multichannel Receiver
16a
Multichannel Receiver
15
30
6

FIG. 2

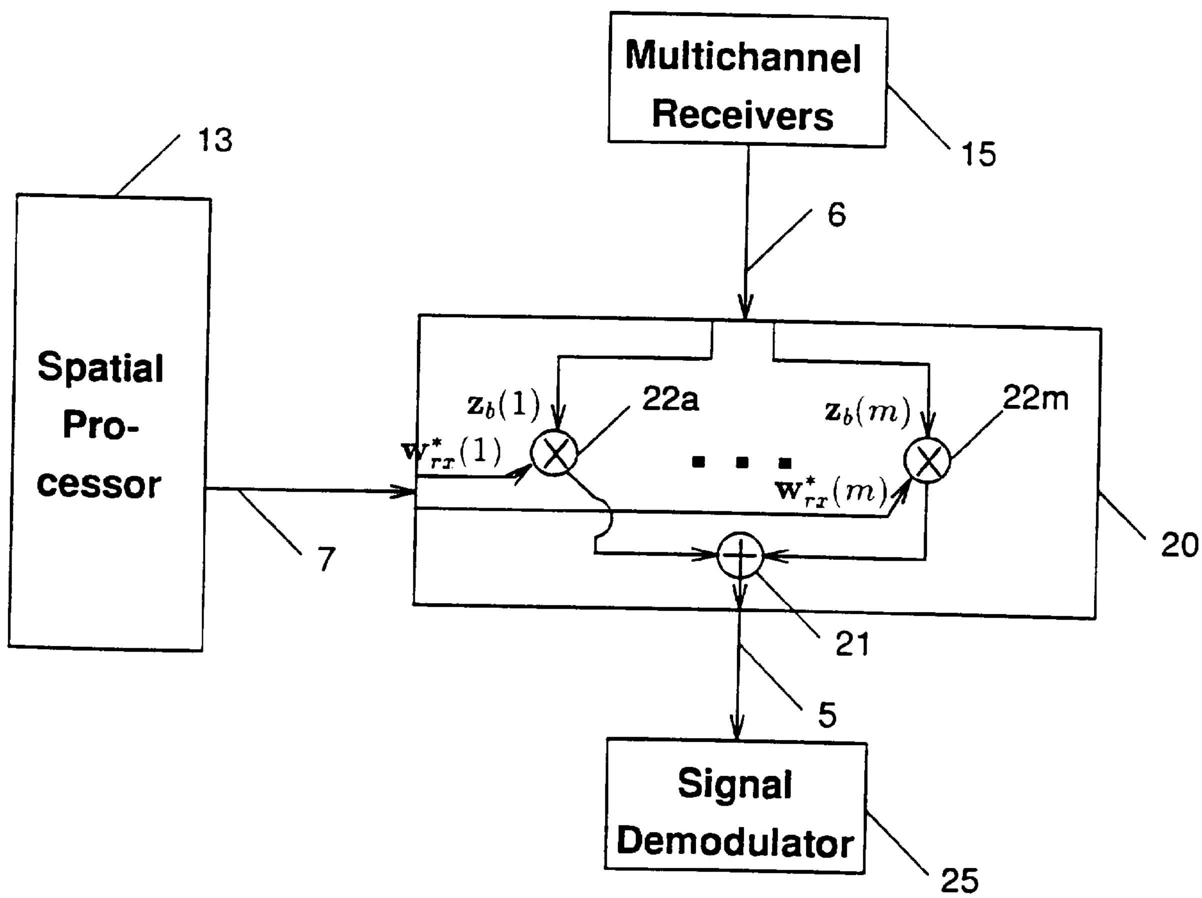

Multichannel Receivers
15
13
6
Spatial Pro- cessor
$z_b(1)$
22a
$z_b(m)$
22m
$w^*_{rx}(1)$
$w^*_{rx}(m)$
7
20
21
5
Signal Demodulator
25

FIG. 3

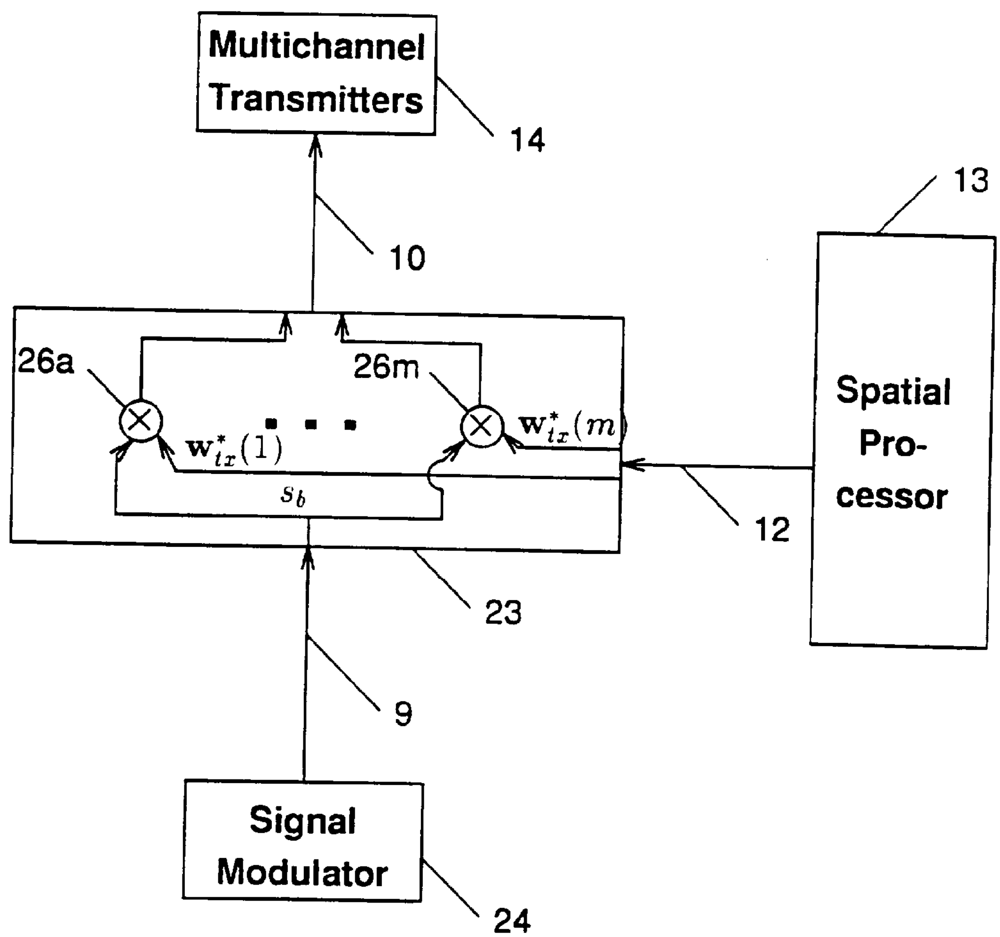
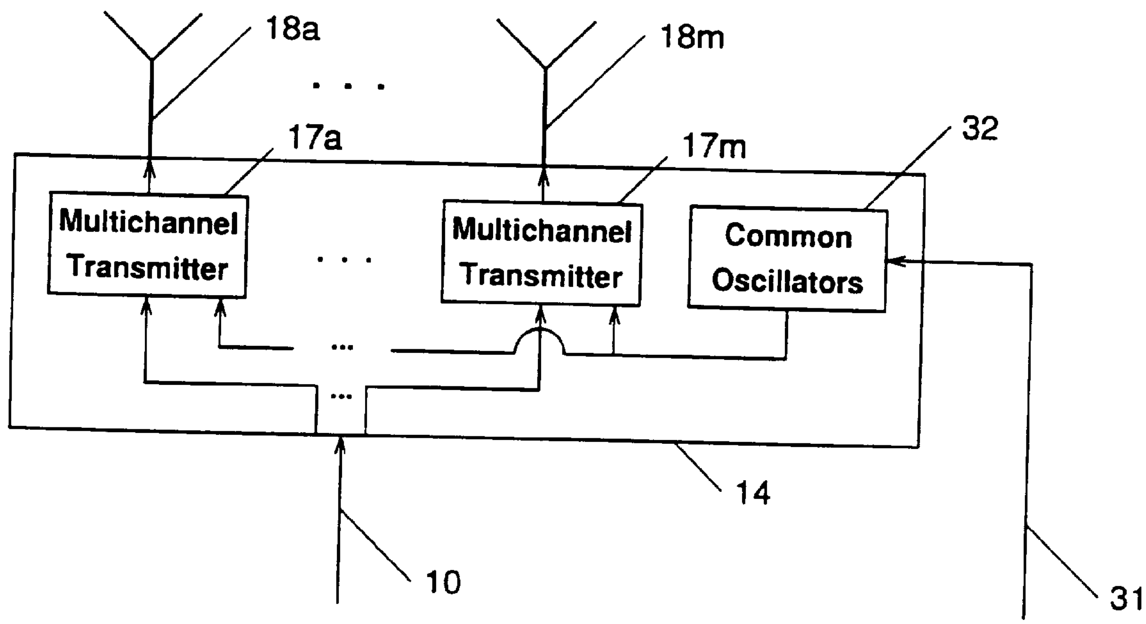

Multichannel Transmitters
14
13
10
26a
26m
$\mathbf{w}_{tx}^*(1)$
$\mathbf{w}_{tx}^*(m)$
s_b
Spatial Pro-cessor
12
23
9
Signal Modulator
24

FIG. 4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17a
17m
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Multichannel Transmitter
Multichannel Transmitter
Common Oscillators
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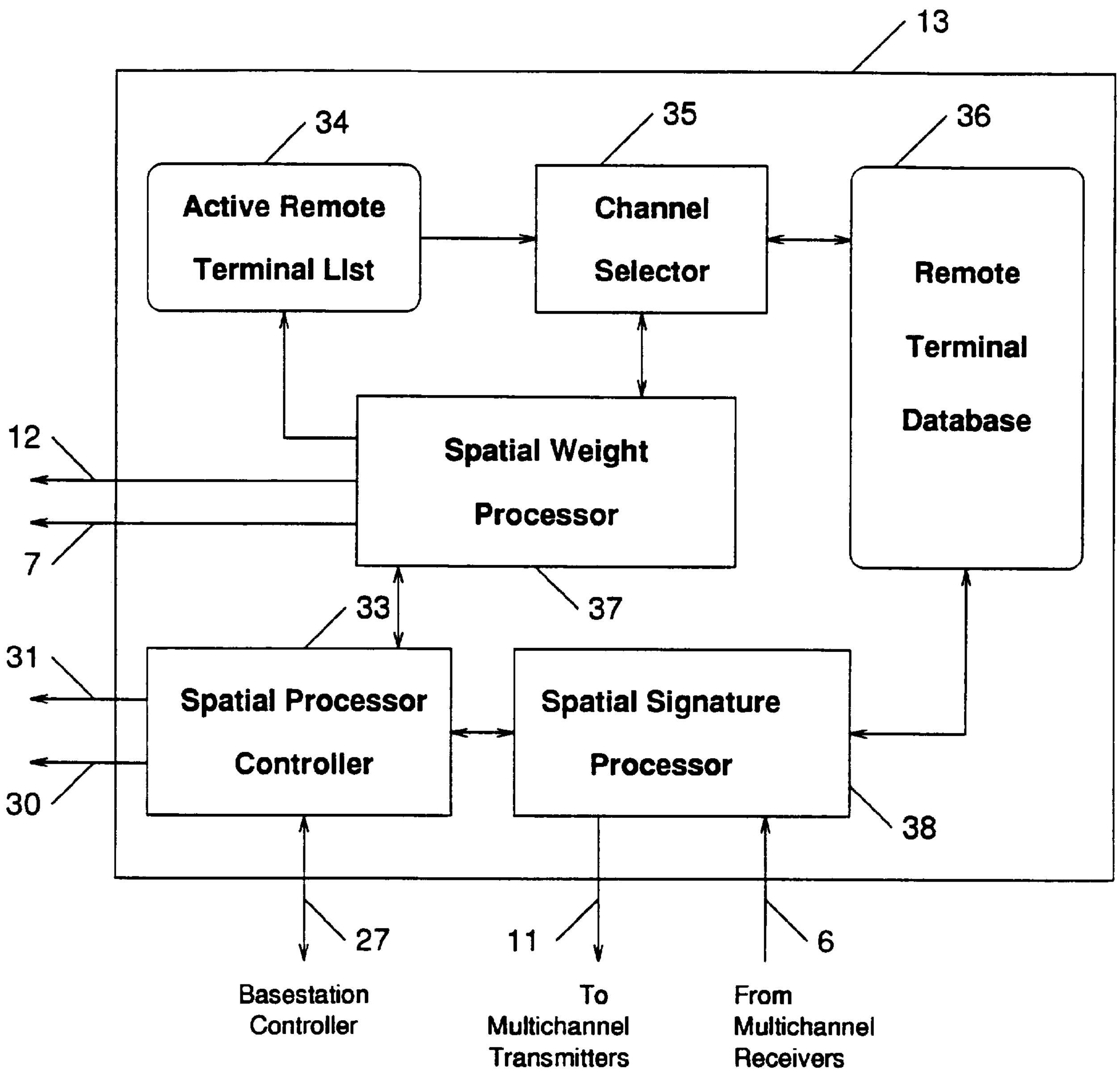
10
31

FIG. 5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Active Remote
Terminal List
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Channel
Selector
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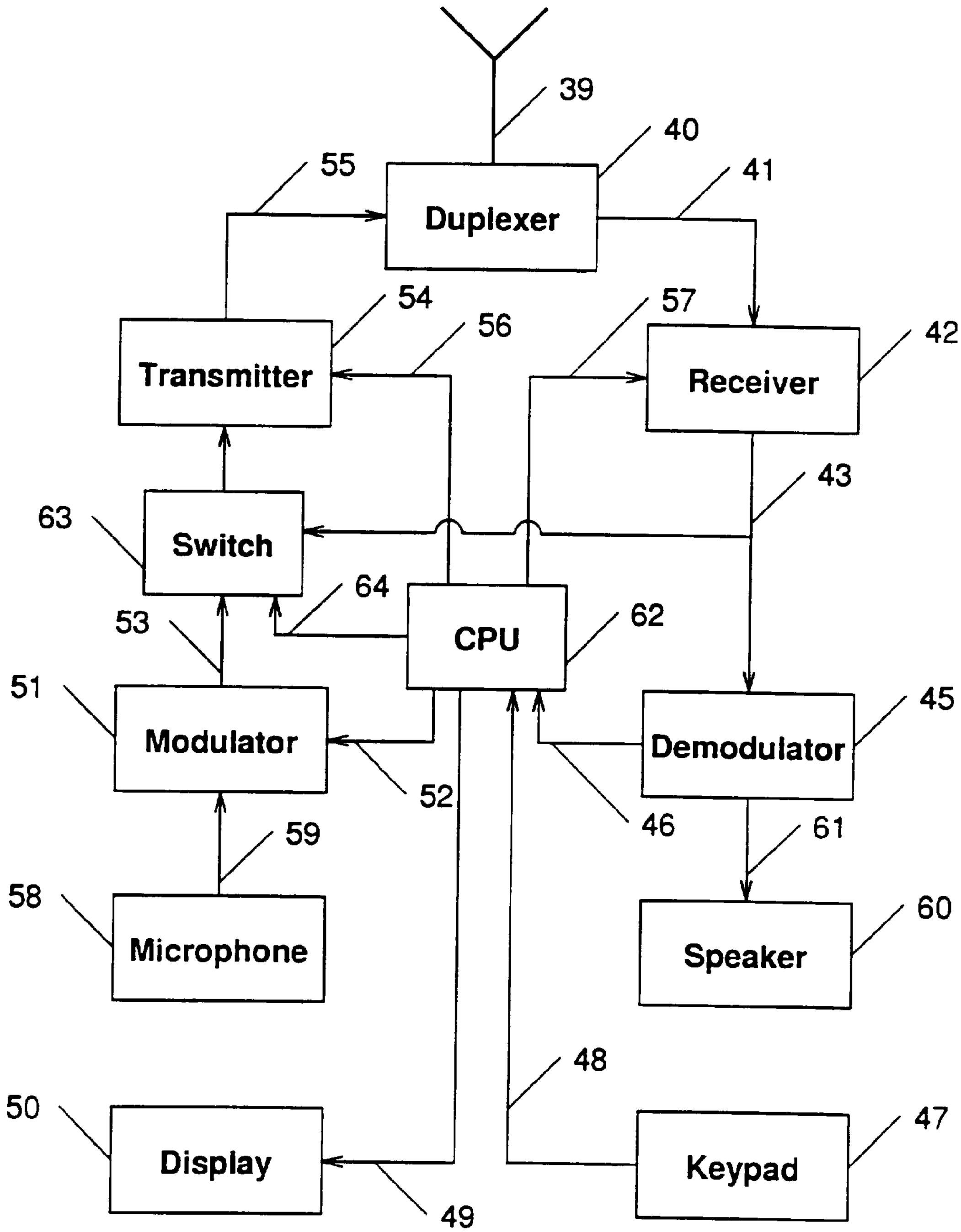
Remote
Terminal
Database
12
7
Spatial Weight
Processor
37
33
31
30
Spatial Processor
Controller
Spatial Signature
Processor
38
27
11
6
Basestation
Controller
To
Multichannel
Transmitters
From
Multichannel
Receivers

FIG. 6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Duplexer
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Transmitter
Receiver
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Switch
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CPU
62
51
Modulator
Demodulator
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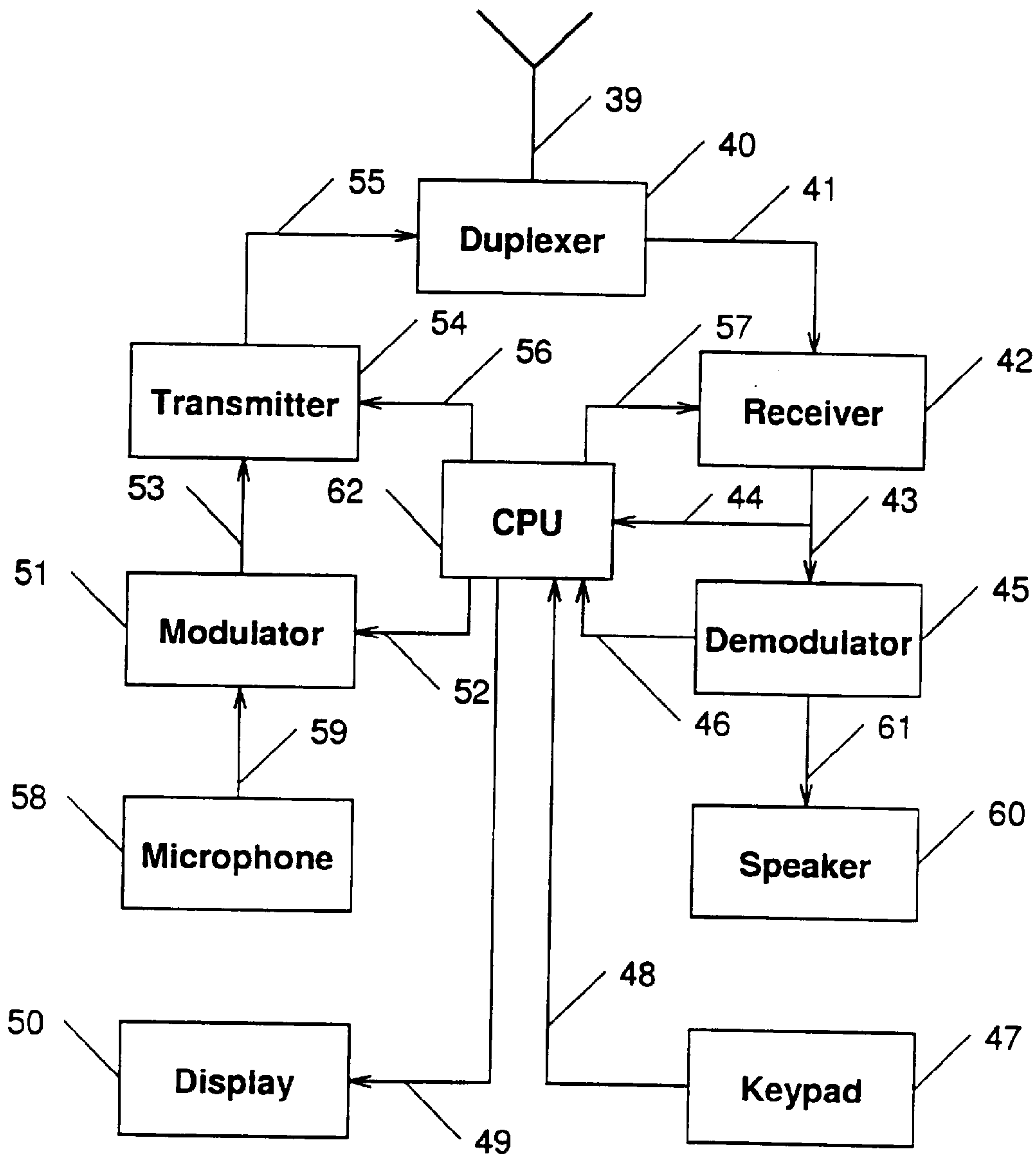
52
46
59
61
58
Microphone
Speaker
60
48
50
Display
Keypad
47
49

FIG. 7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Duplexer
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Transmitter
Receiver
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CPU
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Modulator
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Demodulator
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Microphone
60
Speaker
48
50
Display
47
Keypad
49

FIG. 8

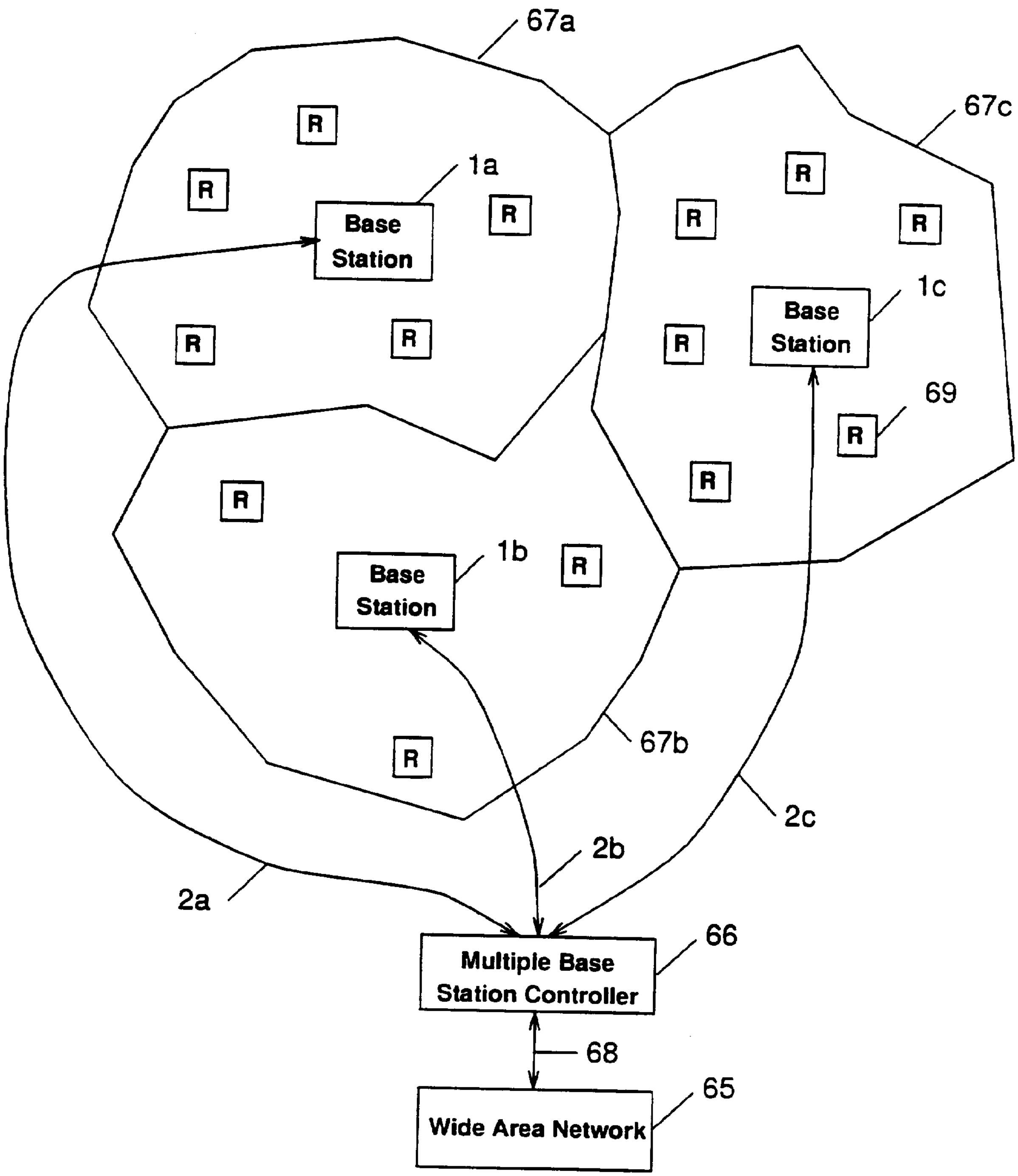
67a
67c
R
R
1a
Base Station
R
R
R
R
R
R
1c
Base Station
R
R
69
R
R
R
1b
Base Station
R
R
67b
2c
2b
2a
66
Multiple Base Station Controller
68
65
Wide Area Network

FIG. 9

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US95/15641

A. CLASSIFICATION OF SUBJECT MATTER

IPC(6) :H04Q 7/20
US CL :370/95.1, 95.3, 119; 342/368, 442, 378, 383, 384; 364/572, 574, 578, 581; 375/200, 205
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 370/95.1, 95.3, 119; 342/368, 442, 378, 383, 384; 364/572, 574, 578, 581; 375/200, 205

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US, A, 5,260,968 (GARDNER ET AL.) 09 November 1993, Fig. 7, 8, and col. 14, line 25, to col. 15, line 41.	1, 6, 9, 10-12, 14, 24, and 31
Y		13
Y	US, A, 5,103,459 (GILHOUSEN ET AL.) 07 April 1992, Fig. 9. and col. 9.	13

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

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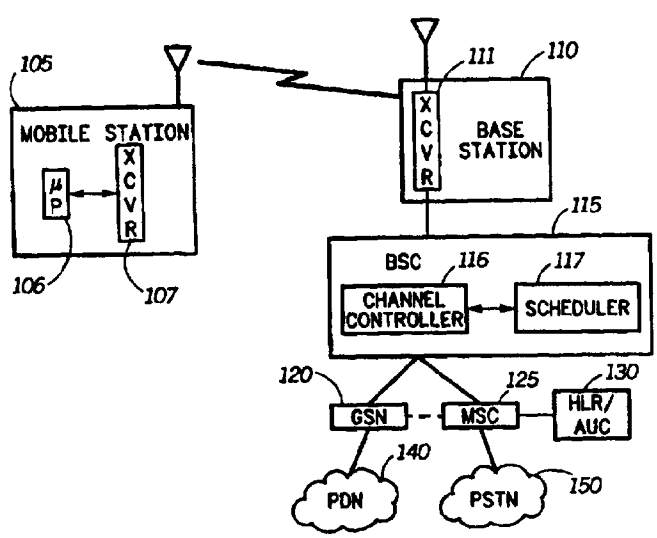

(57) Abstract

A method and apparatus for accessing a communication system relies on the use of varying access probabilities for subscribers or messages of varying priority. A serving infrastructure entity (110) determines access probabilities in response to known system parameters like the current rate of access attempts for each priority class of user/message. Values representative of these access probabilities are then transmitted to the subscriber unit(s) (105), for example by use of a system broadcast channel or control channels. These values are then used by the subscriber units in determining when to access an uplink channel. A temporal and/or proportional priority distribution approach is preferably used in determining the access values. As a result of this contention-based prioritization, an expedited access is achieved by higher priority units/traffic, thus increasing their throughput.

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METHOD AND APPARATUS FOR COMMUNICATION SYSTEM ACCESS

Related Applications

The present application is a continuation-in-part of co-pending U.S. application serial nos. 08/495,385 filed June 28, 1995, and 08/522,649 filed September 1, 1995, both commonly assigned together with this application to Motorola, Inc.

Field of the Invention

The present invention relates to communications and more particularly an imp and Terri ommunicating data in a wireless communications system.

Background

The last 10 years have seen a tremendous increase in the demand for wireless networks capable of handling data communications. Unlike voice services, such as the GSM (Global System for Mobiles) cellular service, in which circuit-switched communications are used because of the sensitivity of users to the timing of oral dialogue, greater efficiencies can be achieved in data communications through the use of packet-switched and hybrid communications. Thus, it is anticipated that a significantly increased throughput can be achieved for shorter traffic by using proposed services such as the GPRS (GSM Packet Radio Service) over traditional circuit-switched wireless technology.

However, with the increased demand for wireless services has also come a demand for faster throughput rates of data traffic, at least for some users. One proposed solution to this need is the use of "quality of service" (QoS) grades for data traffic. By designating a particular data message with a high QoS grade or priority, users who have the need for rapid

end-to-end delivery of their data will have their data delivered ahead of lower QoS data. On the other hand, users who do not want to pay the higher QoS rates and can tolerate longer end-to-end delays can designate their data traffic with a lower QoS grade.

A key problem in implementing this type of service for wireless data communications is the delay in obtaining access to a wireless channel. This problem arises because there are only a limited number of channels (or in the case of TDMA (time division multiple access) systems like GSM, subchannels/time slot sets) available for any given base station service area. Any delay in access will mean a decrease in the time the subchannels are available for actual data transmissions. Further, as the system approaches peak loading, there may well be many more mobile stations (MSs, or more generally subscriber units) attempting to gain access than can be accommodated by the system.

In order to reduce access delay in other wireless systems a number of medium access control (MAC) protocols have been proposed, including both non-contention systems, and well-known contention systems like ALOHA, Slotted-ALOHA, reservation ALOHA, CSMA (Carrier-Sense Multiple Access), DSMA (Digital-Sense Multiple Access), PRMA (Packet Reservation Multiple Access) and QCRA (Queued Contiguous Reservation Aloha). Enhancements to such systems have also been proposed using control algorithms to modify access probabilities. Thus, e.g., pseudo-Bayesian control techniques have been suggested to modify slotted-ALOHA systems based on the number of access attempts per given time period. Using such a technique, a base station might broadcast a value $p = \beta/v$ periodically, where β is a constant and v is an estimate of the current number of ready communication units (e.g., meaning those communication units with data to transmit at that time (e.g., a burst period)). A ready user transmits an

access request with probability p during any available access burst period.

A problem with the standard prior art approaches is that any given access scheme is applied to all units equally. Even where some QoS scheme was used in assigning traffic channels, accessing the system may take significantly longer during higher loading, making for undesirable delays for the high priority traffic.

There remains therefore a need for an improved means for data communications in wireless systems that solves these and related problems.

Brief Description of the Drawings

FIG. 1 is a block diagram of a wireless communications system according to first and second embodiments of the invention;

FIG. 2 is a diagram illustrating messaging between different functional entities of the wireless communications system of FIG. 1;

FIG. 3 is a state diagram illustrating transition states for access of the subscriber unit in the wireless communications system of FIG. 1;

FIG. 4 is a table illustrating access control parameters for use according to the first embodiment of the invention;

FIG. 5 is a diagram illustrating an uplink multiframe communication channel structure for use according to the first embodiment of the invention;

FIG. 6 is a a diagram illustrating an GPRS access channel structure for use according to a second embodiment of the invention.

Detailed Description of the Drawings

These problems and others are solved by the improved method and apparatus according to the invention. A presently preferred embodiment of the invention is a system for controlling access through the use of varying access probabilities for subscribers of varying priority. This would typically start with a serving base station determining access probabilities (e.g., p_{hi} and p_{lo} where there are two classes of subscribers) in response to known system parameters like the current rate of access attempts for each QoS class. Values representative of these access probabilities are then transmitted to the subscriber unit(s), for example by use of a system broadcast channel or control channels. These values are then used by each subscriber communication unit in determining when to access a communication resource, e.g., an uplink channel. In calculating these values, one may use, e.g., a temporal or a proportional priority distribution as more fully described below. As a result of this contention-based prioritization scheme, an expedited access is achieved by higher priority units, thus increasing the overall throughput.

Turning now to FIG. 1, there is generally depicted a wireless communications system 100 having one or more subscriber units (i.e., mobile station (MS) 105) communicating via base station transceiver 111 of base station (BS) 110 and base station controller (BSC) 115. The subscriber unit may be of such diverse types as dedicated data units (e.g., personal digital assistants (PDAs)), radiotelephones (including those adapted for coupling with data terminals like portable computers), or wireless adapter devices (e.g., wireless modems adapted for coupling with computers, message pads, etc.), and the like. In any event, the subscriber unit includes a transceiver 107 and processor 106 appropriately programmed for wireless data communications according to a serving systems protocols. In the illustrated case a combined GPRS-GSM system is shown, although it will be recognized that the

embodiments discussed herein are equally applicable to any other wireless communications system, including CDPD (cellular digital packet data), CDMA (code division multiple access), data systems like ARDIS or RAM, etc. Thus, the portion of the GSM system servicing voice/short messaging subscribers includes an MSC (mobile switching center) 125 connected to an HLR/AuC (home location register/authentication center) 130 and PSTN (public switched telephone network) 150. The GPRS portion includes a GSN (GPRS service node) 120 connected to a packet switched PDN (public data network). GSN 120 includes all information necessary for appropriate routing of data messages; it may alternatively be coupled to MSC 125 to allow access to higher layer user information stored at a common platform such as HLR 130. BSC 115 includes a channel controller 116 and scheduler 117, along with typical BSC circuitry. Alternatively, the controller can be co-located with the base station 110, or distributed elsewhere to a further infrastructure entity, depending on the system design employed. Further, the base station 110 should be understood as illustrative of, and thus meaning, any communication unit operable for serving plural other communication units, not just a central communication unit of a wireless service area or cell.

The operation of this system can be further understood by additional reference now to FIGS. 2 and 3. In FIG. 2, the control/traffic communications flow among the MS 210, BS subsystem 220 and GSN 230 is generally depicted. Both MS 210 and BS/BSC 220 include access controllers (212 and 222 respectively) and data transmission controllers (214 and 224 respectively), which GSN 230 includes an access manager 232. Current configuration parameters, including loading and service priority information derived from usage and access channel statistics, is communicated between the GSN 230 and BS/BSC access controller 222. Based on this information

access control parameters are determined and broadcast in an access control message via the BS to MSs in the BS service area. These access parameters are preferably the current service priority level and access probability parameters. When the MS data transmission controller 214 receives a data transfer request, a transmission request message is transferred to the access controller 212 (i.e., moving from state 310 to monitor state 320 of FIG. 3). Based on the access control parameters and its data message priority, MS access controller 212 determines whether to send an access message/request (state 330) or backoff (state 325), and BS/BSC access controller 222 determines whether to allocate communications resource(s) in response to such a request. After a time-out period and no response, MS 210 again retries access (state 335). Upon allocation, access controller 222 notifies both MS 210 and data receiver controller 224 of the subchannel allocation, and the data transmitter controller 214 and data receiver controller 224 commence transfer of the data (state 340).

In order to facilitate transfer of higher priority data, a contention-based procedures is employed to limit MS access requests. A preferred contention-based procedure, illustrated with reference to FIGS. 4 through 6, uses two or more access probabilities (e.g., p_{hi} and p_{lo}, or p_1, p_2, .. p_n if more than two probability levels) to control the access attempts by different priority classes of subscribers. Two particularly useful approaches for determining the access values are the following proportional and temporal priority distribution approaches. In a preferred proportional priority distribution, one starts with a pseudo-Bayesian algorithm modified to consider a three state feedback: idle, success or collision. While the best approach would be to establish the priority based access probability p for one of all current ready users n (such that p = 1/n), the value of n is often unknown. This can be approximated by, e.g., a known pseudo-Bayesian algorithm,

derived by approximating the value of n using a Poisson distribution of backlogged users having mean of n. Since this only takes into account collision vs. no collision states, this can be further modified to take into account the effects of capture by taking into consideration the value (e.g., the constant ß) at which the maximum channel throughput occurs, such that $p = \beta/v$. For slotted-ALOHA (S-ALOHA) in GPRS, this has been approximated as about 1.39; one skilled in the art will know how to determine this parameter for other protocols and system conditions.

Following calculation of p, the base station determines a separate probability for the different priority groups. A presently preferred approach is to have a smaller number of priority groups for access purposes than the number of defined QoS classes. This approach reduces the overhead in the repeatedly broadcast p vectors, when separate access values may not be necessary for efficient access. For example, in GPRS proposal has been made for five QoS classes, based on the delay time for end to end throughput. These classes are illustrated in the following table:

	128 octet packets		1024 octet packets	
QoS Class	mean delay	95% delay	mean delay	95% delay
Class 1	0.5 sec	0.7 sec	1.2 sec	1.4 sec
Class 2	0.5 sec	2.5 sec	3 sec	1.5 sec
Class 3	5 sec	25 sec	15 sec	75 sec
Class 4	50 sec	250 sec	75 sec	375 sec
Class 5	best effort	best effort	best effort	best effort

Because there is a significantly longer delay tolerance for classes 3-5 than for classes 1-2, one can advantageously use two access probabilities--a regular access probability for the group of communication units from classes 3 through 5, and an expedited access probability for the group of communication units from classes 1 and 2, having a higher priority than the other group.

A base station (or BSC, GSN or other controller, depending on the implementational assignment of control features) preferably determines an access probability vector (e.g., one or more words representative of the plural access probabilities or p-persistence values) using the calculated p and additional access parameters. In the preferred embodiment for proportional priority distribution the BS also maintains a running count of the proportion of expedited versus regular access messages received over a predetermined time period. The proportion of regular access requests to the total number of access requests (i.e., regular plus expedited) may be termed α, where $0 < \alpha < 1$. The proportion of expedited access requests is then $1 - \alpha$. Alternatively, depending on the implementation one may find it advantageous to keep the value of α within some defined min-max boundaries, for example $\alpha_{min} \leq \alpha \leq \alpha_{max}$, where $\alpha_{min} = 0.1$ and $\alpha_{max} = 0.9$.

The base station then preferably calculates the group probability values as

$$p_{hi} = (1 + \alpha) \times p, \text{ and} \qquad \text{Eq. 1}$$

$$p_{lo} = \alpha \times p. \qquad \text{Eq. 2}$$

This algorithm does not alter the overall probability that an access request will be transmitted during a given burst period, and therefore does not alter the effectiveness of the optimized pseudo-Bayesian technique. That such is the case can be shown by considering the following relationships, starting with the probability $p = \beta/v$ that each ready user will

transmit within an individual burst period, where the number of ready users is estimated by v and the optimal throughput is achieved when $pv=\beta$. When all ready users are categorized in two priority groups, high and low, such that $v = v_{hi} + v_{lo}$, then the proportion of lo priority ready users is

$$\alpha = v_{lo}/v. \qquad \text{Eq. 3}$$

The two probability values p_{hi} and p_{lo} are then determined as

$$p_{hi} = (1 + \alpha) \times p = (1 + \alpha)\,\beta/v \text{ and} \qquad \text{Eq. 4}$$

$$p_{lo} = \alpha \times p = \alpha\beta/v, \qquad \text{Eq. 5}$$

where p_{hi} represents the probability that each of the v_{hi} ready users transmits within an individual burst period, and p_{lo} represents the probability that each of the v_{lo} ready users transmits within an individual burst period. From the above it can be seen that the sum of all transmit probabilities remains constant β no matter what the proportional distribution of high and low priority ready users is; i.e.,

$$\beta = pv = (p_{hi} \times v_{hi}) + (p_{lo} \times v_{lo}). \qquad \text{Eq. 6}$$

Substituting the values for p_{hi} and p_{lo} above yields

$$\beta = pv = ((1 + \alpha)pv_{hi}) + (\alpha p v_{lo}), \qquad \text{Eq. 7}$$

which reduces to

$$v = (1 + \alpha)v_{hi} + \alpha v_{lo},$$

$$= v_{hi} + (v_{lo}v_{hi}/v) + (v_{lo}v_{lo}/v). \qquad \text{Eq. 8}$$

This further reduces from:

$$v_{lo} = v - v_{hi} = (v_{lo}v_{hi}/v) + (v_{lo}v_{lo}/v), \text{ to}$$

$$v \times v_{lo} = v_{lo}(v_{hi} + v_{lo}), \text{ to}$$

$$v = v_{hi} + v_{lo}. \qquad \text{Eq. 9}$$

Thus, it is shown that this algorithm does not alter the overall probability that an access request will be transmitted during a given burst period, and does not alter the effectiveness of the optimized pseudo-Bayesian technique. It therefore better insures that expedited access requests will be transmitted with a higher probability than regular access requests, and meets such preferred system design criterion as (1) increasing loads from low priority users without degrading performance of high priority users; (2) permitting equal priority messages to contend fairly (e.g., by a FIFO (first in first out) rule); and (3) keeping overhead and volume of control information to a minimum.

Again, while the above embodiment has been described in connection with a two group priority scheme, any number n of groups can be used depending on the design criterion for a given system. FIGS. 4 and 5 illustrate the use of n = 4 groups/ levels of access probability. The probability values p_1, p_2, ... p_n for each group are again determined by the appropriate infrastructure entity (e.g., the BS or BSC) in response to known system parameters like the current rate of access attempts for each group. Values representative of these access probabilities are then transmitted to the subscriber unit(s), for example by use of a system broadcast channel or control channels. These values could simply be the probability values, or could be a more convenient format for efficient communication such as the closest integer w_n (an access window period) to the inverse of the p_n value, with the access values appropriately formatted, e.g., as one or plural control words (i.e., an access control vector).

Each MS then determines whether to transmit during a current access period based on the received access control vector. Where the vector includes access window values such as in FIG. 4, the values are preferably applied by first selecting the value applicable to priority class of the subscriber or, if appropriate to the system, a queued packet or

message. A random number or the like is then preferably generated and applied to the selected value to generate a delay value. The subscriber then counts this delay value number of allowed burst periods (i.e., data time slots available for access) before transmitting its access/reservation request; counting is suspended during periods when the MS is not allowed access. Thus, as illustrated in FIG. 5, a priority level 1 packet will have a maximum wait period t_1 (501) substantially shorter than periods t_2 through t_4 (502-504) for priority levels 2 through 4. However, the actual burst period 505 at which an access request is sent could be the same for data traffic of all priority levels (at least those greater than the minimum priority level), although with differing probabilities of occurrence. The use of a random/pseudorandom number or similar user differentiating value permits different outcomes for plural subscribers, so all do not attempt access at the same time. This reduces the collision potential, particularly when service is denied to a whole group for a given period (such as happens in the temporal priority approach below) and then made available again. Alternative uses of a differentiating user-generated value such as a random number will be apparent to a skilled artisan; e.g., instead of determining a window period, between 0 and 1 could be generated each allowed burst period, with an access attempt being permitted if the number is greater than the applicable probability value and otherwise inhibited.

A second embodiment may alternatively be used, in which a temporal priority distribution is employed. In one form, as illustrated by FIG. 6, separate expedited and regular periods are provided on, e.g., a random access channel in which to make access attempts. Assuming for illustration that there are two priority access groups, the BSC (or other appropriate infrastructure entity like a GSN) determines two estimates of the number of ready users, v_{hi} being the estimate of ready high priority users and v_{lo} being the estimate of ready low priority

users. Using a pseudo-Bayesian calculation, the access probabilities are $p_{hi} = ß/v_{hi}$ and $p_{lo} = ß/v_{lo}$. Each access channel, such as channel 600, is then preferably apportioned into plural (two in this case) access periods, one group of bursts being for expedited access requests and the other being for both regular and expedited access requests. The expedited access period 601 is variable in length and high priority users (e.g., QoS class 1 and 2 subscribers or packets) contend equally using transmit probability p_{hi}. The regular access period 602 has a fixed length of Nr frames and regular priority users contend equally using transmit probability p_{lo}. The base station preferably keeps track of the current estimate of high priority ready users v_{hi} and regular ready users v_{lo} using the pseudo-Bayesian algorithm described above. During the expedited access period 601 the base station broadcasts the value of $p_{lo} = 0$ (indicating that no regular access requests should be transmitted) and $p_{hi} = ß/v_{hi}$. During the regular access period 602, the base station broadcasts the value of $p_{hi} = p_{lo} = ß/v$. In other words, both expedited and regular access requests may be transmitted during this period 602 using the same transmit probability.

The transition from expedited to regular access periods preferably occurs as follows: when the base station determines that $p_{hi} = 1$ and the channel status is idle for at least one access burst period, then the regular contention period may begin and continue for some fixed duration (Nr frames). The base station knows to begin the regular access period when $p_{hi} = ß/v_{hi} = 1$, because if any ready users remain with an expedited request the burst period status would not be idle (i.e. it would be a success or collision status). Therefore this algorithm provides a level of guarantee that there are no remaining expedited requests to be transmitted when the regular contention period begins, and that an expedited request should not wait longer than Nr frames for an expedited channel access period. The base station may, of course, alter the

frequency of the expedited access periods (i.e. the value of Nr), since it controls the broadcast values p_{hi} and p_{lo}. An expedited access period occurs whenever $p_{lo} = 0$, and a regular access period occurs whenever $p_{lo} > 0$.

Alternately, a hybrid of both the temporal and proportional priority distribution approaches may be employed where there are more than two priority groups. Thus, in the case illustrated by FIGS. 4 and 5, a temporal distribution can be effected by setting the broadcast access probability of one or more of the lower priority classes to 0. The remaining priority groups would apply the applicable access value to determine when to attempt access. Alternately, rather than setting some values to 0 an inhibit message can be sent as part of the access control parameters message. These approaches are particularly advantageous in taking advantage of changing loading conditions, without forcing all classes of the lowest group to contend for a significantly shortened access resource. For example, as loading increases a best efforts service (BES, class 5 in GPRS) could be readily set to probability 0 without affecting the QoS delays for classes 1-4. As loading continues to increase, classes 4 to 2 could be progressively shed by setting their probability to 0 as needed to maintain access for the higher priority classes. Of the classes still being served at any time, these users would continue determining when to send an access burst using the proportional priority approach above. But, unlike the temporal priority approach above, when loading is only moderate so as to permit class 1-4 but not class 5 service, there is no requirement for inhibiting all the low group users, i.e., those units that are a member of class 3 or 4, along with class 5 users. If desired, periodic higher priority access periods could be permitted even during moderate loading, set, e.g., to allow an access attempt for users of a given class within some predetermined period related to their QoS delay time. For example, even where there continue to be sufficient class 3

and higher users to otherwise result in class 4 users having a 0 access probability, every 50 seconds (i.e., the guaranteed mean delay period, and 1/5 of the 95% delay period for class 4 users) a period for class 4 access attempts is provided. Further refinements are also possible, such as by allowing the infrastructure entity to vary the access probabilities and inhibits for different channel/subchannel resources as opposed to all resources served, e.g., by a given BS. Likewise, a subscriber's class membership need not remain static, so the group for which a unit is currently a member can be determined by any convenient means such as a unit class, a user class, or even a user-selected priority class for a currently pending/queued data message. Thus, if the subscriber wants to send traffic and a comparison of the access value/priority service level for other subchannels shows that no subchannel is available at the specified priority grade of service/group, the subscriber may optionally chose to either automatically or via user input alter the data priority (and billing) level to a level high enough to permit access requests. Additionally, if other packets of higher priority are queued in the MS, the MS may chose to transmit the higher priority data packets ahead of a currently queued lower priority packet.

One skilled in the art will appreciate that any one of numerous well-known access channel structures and post-contention prioritization schemes may be employed with the invention, each with varying merit depending on the specific design parameters of a given communication system. Thus none are presently preferred, even in the context of GPRS given the presently undecided nature of its standard, but a skilled artisan will be able to readily determine which to apply.

While the invention has been described in conjunction with specific embodiments thereof, it is evident that many alterations, modifications, and variations will be apparent to

those skilled in the art in light of the foregoing description. For example, while processor 106, channel controller 116 and scheduler 117, and other circuits, are described in terms of specific logical/functional circuitry relationships, one skilled in the art will appreciate that such may be implemented in a variety of ways, such as appropriately configured and programmed processors, ASICs (application specific integrated circuits), and DSPs (digital signal processors). Further, the invention is not limited to the illustrated cellular systems, but has applicability to any communication system having an access protocol for communication resources (including wireline or fiber optic channels) and differentiated service. It should further be understood that for purposes of this application, a first device or component is responsive to or in communication with a second unit or component regardless of whether the first and second units are directly coupled or indirectly coupled, such as via intermediate units, including switches that operatively couple the units for only a segment of time, as long as a signal path can be found that directly or indirectly establishes a relationship between the first and second units. Thus, it should be understood that the invention is not limited by the foregoing description of preferred embodiments, but embraces all such alterations, modifications, and variations in accordance with the spirit and scope of the appended claims.

We claim:

Claims

1. A method of controlling access to a communication resource comprising:

(a) determining from system parameters a first access value for a first group of communication units and a second access value for a second group of communication units, the first group having a higher priority for communication than the second group; and

(b) transmitting an access control message including the first and second access values.

2. The method of claim 1, wherein the system parameters include information regarding access attempts by the first and second groups to the communication resource within a predetermined period of time, and step (a) comprises determining the first and second access values from the information.

3. The method of claim 2, wherein the first and second access values are first and second access probability values, respectively, and step (a) comprises determining the first and second access probability values based on the system parameters.

4. The method of claim 1, wherein step (a) further comprises:

(i) determining an approximate number v of ready communication units of both first and second groups;

(ii) determining a first access probability p_1 for the first group based on the approximate number v of ready communication units, a proportion a of access requests by the

first group to a total number of access requests by the first and second groups during a predetermined period, and an approximate maximum channel throughput value ß, such that $p_1 = (1 + \alpha)(\beta/v)$; and

(iii) determining a second access probability p_2 for the second group based on v, α and ß such that $p_2 = \alpha\beta/v$.

5. The method of claim 1, wherein step (a) further comprises:

(i) providing plural access periods, including a first access period when the second group is inhibited from sending access messages and a second access period when both the first and second groups can send access messages.

6. The method of claim 5, wherein the first and second access values are first and second access probabilities, respectively, and step (a) further comprises, during the first access period:

(ii) determining an approximate number v_1 of ready communication units of the first group;

(iii) determining the first access probability p_1 for the first group based on the approximate number v_1 of ready communication units and an approximate maximum channel throughput value ß, such that $p_1 = \beta/v_1$; and

(iii) setting the second access probability p_2 for the second group to 0 in order to inhibit the second group from sending access messages.

7. The method of claim 5, wherein the first and second access values are first and second access probabilities, respectively, and step (a) further comprises, during the second access period:

(ii) determining an approximate number v_1 of ready communication units of the first group and an approximate number v_2 of ready communication units of the second group;

(iii) determining the first access probability p_1 for the first group based on the approximate number v_1 of ready communication units and an approximate maximum channel throughput value ß, such that $p_1 = ß/v_1$; and

(iv) determining the second access probability p_2 for the second group based on v_2 and ß, such that $p_2 = ß/v_2$.

8. The method of claim 1, wherein the first group of communication units comprises a first class of communication units having a first quality of service level, and step (a) comprises determining the first and second access values so as to maintain the first quality of service level for the first group.

9. The method of claim 1, wherein the first group of communication units comprises a first class of communication units having messages to send at a first quality of service level, and step (a) comprises determining the first and second access values so as to maintain the first quality of service for any of said messages of the first group.

10. A method of accessing a communication resource of a base station comprising, at a first communication unit:

(a) receiving an access control message for the communication resource including a first access value for a first group of communication units and a second access value for a second group of communication units, the first group having a higher priority for access to the communication resource than the second group;

(b) selecting one of the first and second access values based on which one of the first and second groups the first communication unit is currently a member; and

(c) determining when to send an access message using said one of the first and second access values selected in step (b), and then sending the access message on the communication resource.

11. The method of claim 10, wherein the first and second access values are first and second access probability values, respectively, and step (b) comprises selecting the first access probability value when the first communication unit is one of the first group of communication units.

12. The method of claim 10, wherein the first and second access values are first and second access probability values, respectively, and step (b) comprises selecting the second access probability value when the first communication unit has a message to send having a current priority grade corresponding to a priority grade of the second group of communication units.

13. The method of claim 12, wherein the access control message includes an inhibit message for the second group, and step (c) further comprises inhibiting the access message in response to the inhibit message.

14. The method of claim 10, wherein the access control message includes an indication that in a current period of plural access periods access messages from the second group are to be inhibited, step (c) further comprising inhibiting the access message in response to the access control message when the first communication unit is one of the second group of communication units.

15. The method of claim 14, wherein the indication is a zero value for the second access value.

16. The method of claim 10, wherein step (c) comprises determining when to send an access message based on a product of said one of the first and second access values selected in step (b) and a pseudorandom value generated by the first communication unit.

17. A communication system having a communication resource for use in accessing the communication system, comprising:

a base station transceiver adapted for communication to plural communication units;

a controller in communication with the transceiver operable for determining from system parameters a first access value for a first group of the communication units and a second access value for a second group of the communication units, the first group having a higher priority for access to the communication resource than the second group; and

wherein the base station transceiver is responsive to the controller to transmit an access control message including the first and second access values.

18. The system of claim 17, wherein the communication resource is at least one communication channel available for use in communicating with the transceiver, and the controller is operable for determining (i) an approximate number v of ready communication units of both first and second groups, (ii) a first access probability p_1 for the first group based on the approximate number v of ready communication units, a proportion α of access requests by the first group to a total number of access requests by the first and second groups during a predetermined period, and an approximate maximum channel throughput value β, such that $p_1 = (1 + \alpha)(\beta/v)$, and (iii) a second access probability p_2 for the second group based on v, α and β such that $p_2 = \alpha\beta/v$.

19. The system of claim 17, wherein the communication resource is at least one communication channel available for use in communicating with the transceiver, and the controller is operable for providing plural access periods, including a first access period when the second group is inhibited from sending access messages and a second access period when both the first and second groups can send access messages.

20. The system of claim 19, wherein the first and second access values are first and second access probabilities, respectively, and the controller is operable for determining, during the first access period, (i) an approximate number v_1 of ready communication units of the first group, (ii) the first access probability p_1 for the first group based on the approximate number v_1 of ready communication units and an approximate maximum channel throughput value β, such that $p_1 = \beta/v_1$, and (iii) setting the second access probability p_2 for the second group to 0 in order to inhibit the second group from sending access messages.

21. The system of claim 19, wherein the first and second access values are first and second access probabilities,

respectively, and the controller is operable for determining, during the second access period, (i) an approximate number v_1 of ready communication units of the first group and an approximate number v_2 of ready communication units of the second group, (ii) the first access probability p_1 for the first group based on the approximate number v_1 of ready communication units and an approximate maximum channel throughput value ß, such that $p_1 = ß/v_1$, and (iii) determining the second access probability p_2 for the second group based on v_2 and ß, such that $p_2 = ß/v_2$.

22. The system of claim 17, further comprising a service node, coupled to the controller, operable for storing information regarding access attempts by the first and second groups to the communication resource within a predetermined period of time and communicating the information to the controller, wherein the controller is further operable for determining the first and second access values from the information.

23. A communication unit for communicating in a communication system comprising:

a transceiver for receiving an access control parameter from a base station of the system; and

a processor operable for determining when to send an access request based on the access control parameter and a current priority level of the communication unit.

24. The communication unit of claim 23, wherein the communication unit is a subscriber unit and the processor is further operable to inhibit sending the access request when the current priority level is less than a current service priority indicated by the access control parameter, and otherwise to determine when to send the access request based on one of plural access values included in the access control parameter and the current priority level of the subscriber unit.

25. The subscriber unit of claim 24, wherein the processor is further operable for determining the current priority level from one of a group consisting of a user priority level or a pending message priority level.

26. The communication unit of claim 23, wherein the access control parameter includes a first access value for a first group of communication units and a second access value for a second group of communication units, the first group having a higher priority for communication than the second group, and the processor is further operable for determining when to send the access request based on which of the first and second access values corresponds to the current priority level of the communication unit.

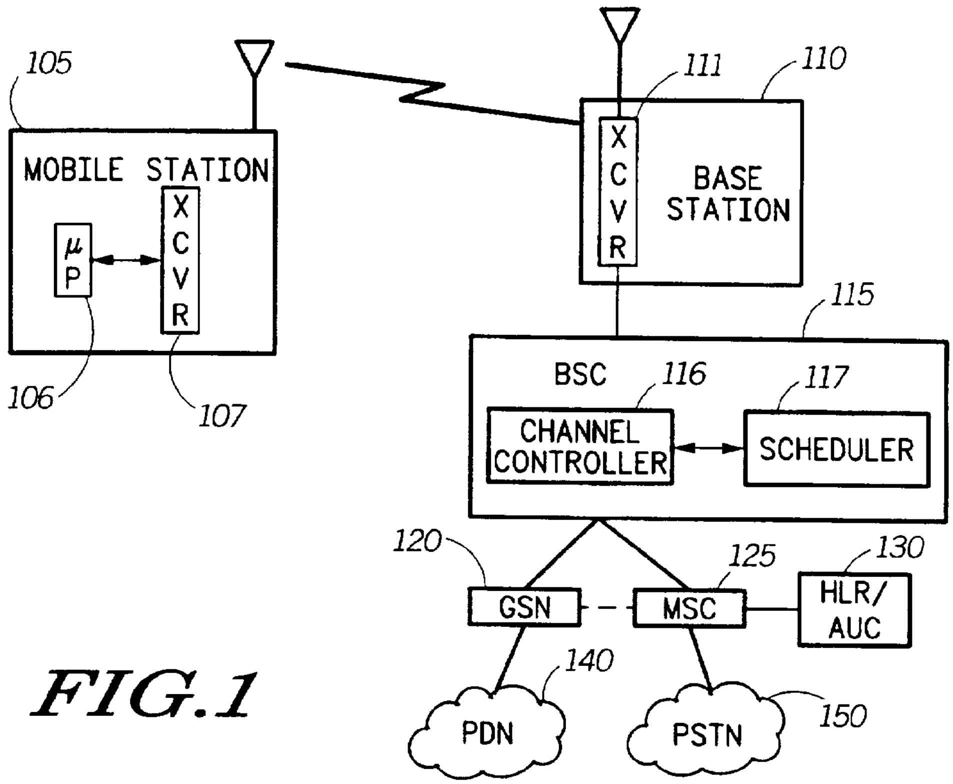

105
MOBILE STATION
μP
XCVR
106
107
111
110
XCVR
BASE STATION
115
BSC
116
117
CHANNEL CONTROLLER
SCHEDULER
120
125
130
GSN
MSC
HLR/ AUC
140
PDN
PSTN
150

FIG.1

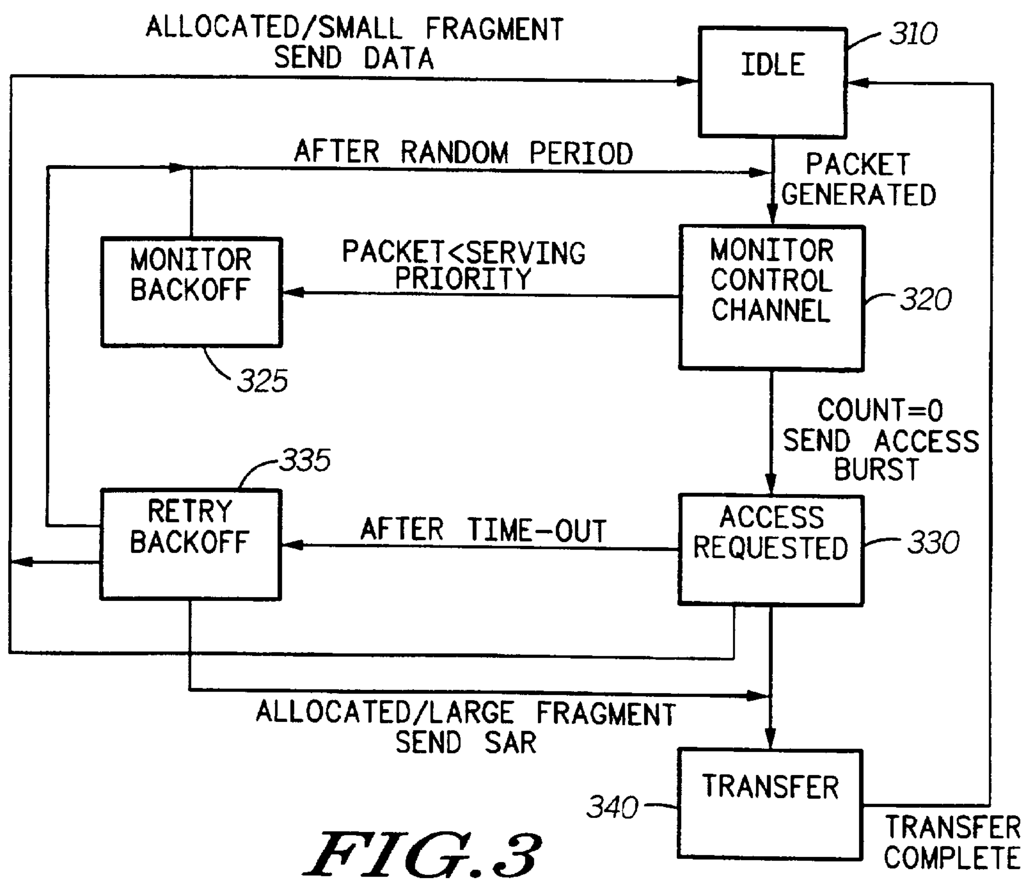

ALLOCATED/SMALL FRAGMENT SEND DATA
IDLE
310
AFTER RANDOM PERIOD
PACKET GENERATED
MONITOR BACKOFF
PACKET<SERVING PRIORITY
MONITOR CONTROL CHANNEL
320
325
COUNT=0 SEND ACCESS BURST
335
RETRY BACKOFF
AFTER TIME-OUT
ACCESS REQUESTED
330
ALLOCATED/LARGE FRAGMENT SEND SAR
340
TRANSFER
TRANSFER COMPLETE

FIG.3

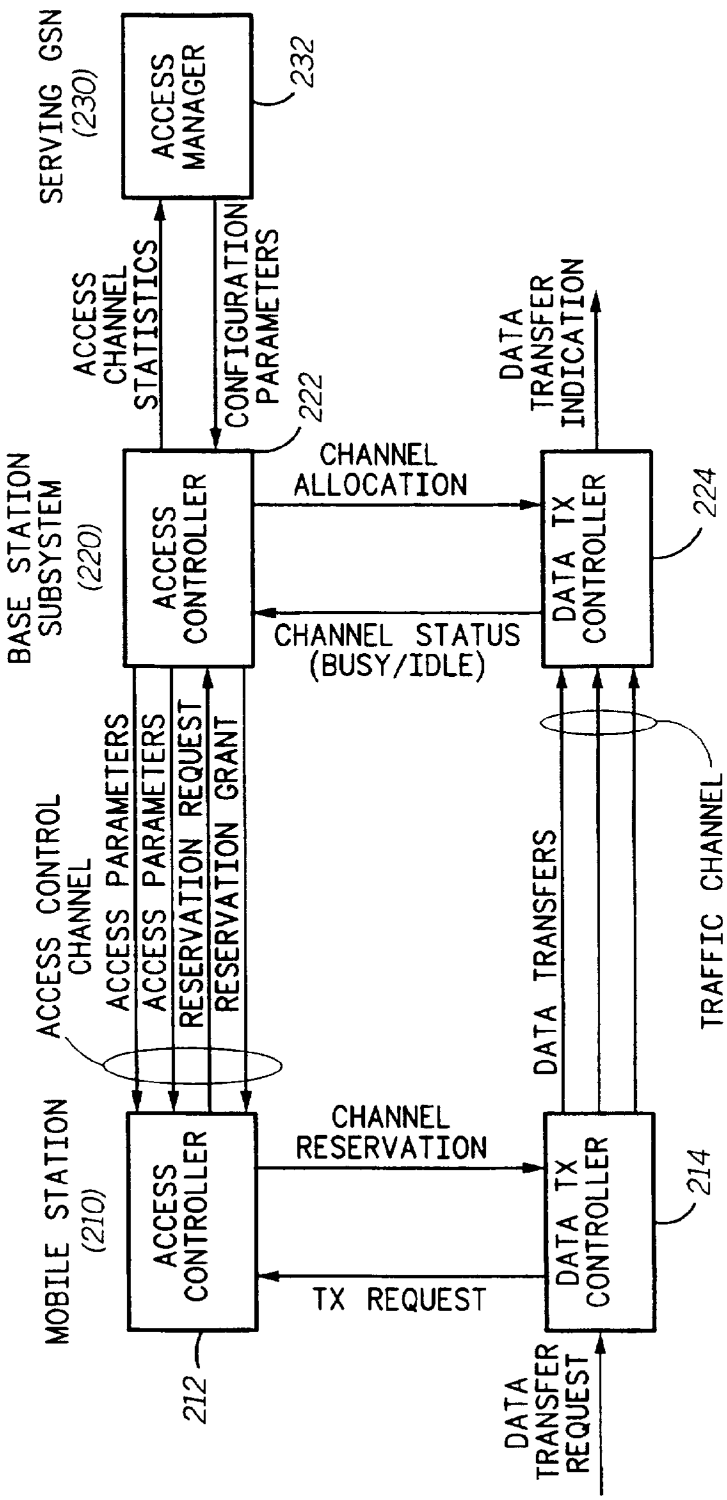
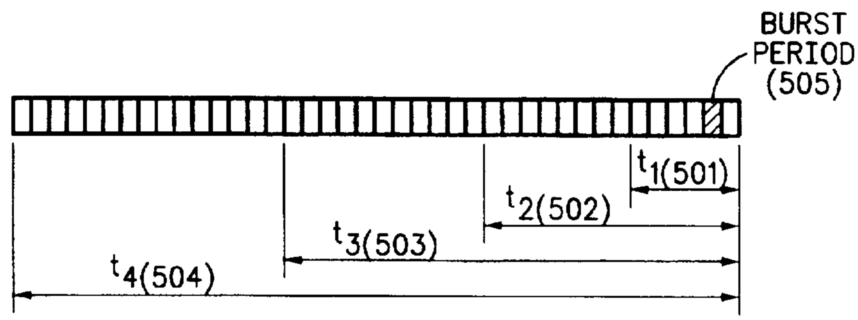

SERVING GSN
(230)
ACCESS MANAGER
232
ACCESS CHANNEL STATISTICS
CONFIGURATION PARAMETERS
BASE STATION SUBSYSTEM
(220)
ACCESS CONTROLLER
222
CHANNEL ALLOCATION
CHANNEL STATUS (BUSY/IDLE)
DATA TX CONTROLLER
224
DATA TRANSFER INDICATION
ACCESS CONTROL CHANNEL
ACCESS PARAMETERS
ACCESS PARAMETERS
RESERVATION REQUEST
RESERVATION GRANT
DATA TRANSFERS
TRAFFIC CHANNEL
MOBILE STATION
(210)
ACCESS CONTROLLER
212
CHANNEL RESERVATION
TX REQUEST
DATA TX CONTROLLER
214
DATA TRANSFER REQUEST

FIG. 2

P-PERSISTENCE PARAMETERS

PRIORITY (N)	P_N	$W_N=1/P_N$
1	.05	20
2	.03	33
3	.025	40
4	.02	50

FIG.4



t_1:PRIORITY 1 ACCESS REQUEST PERIOD
t_2:PRIORITY 2 ACCESS REQUEST PERIOD
t_3:PRIORITY 3 ACCESS REQUEST PERIOD
t_4:PRIORITY 4 ACCESS REQUEST PERIOD

FIG.5

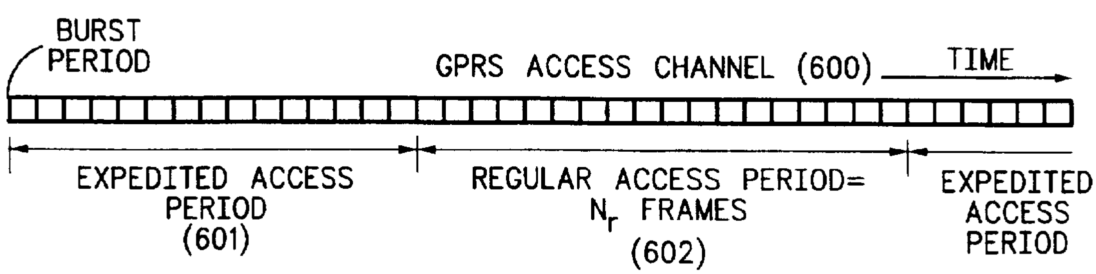


FIG.6

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US96/18591

A. CLASSIFICATION OF SUBJECT MATTER

IPC(6) :H04B 7/204
US CL :370/346, 444, 461, 462
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 370/230, 346, 347, 443, 444, 449, 461, 462; 304/825.51

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

NONE

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

NONE

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US, A, 5,436,905 (LI ET AL) 25 JULY 1995, col. 4 lines 36-54.	1-3, 5, 8-12, 16, 17, 19, 22-26
A	US, A, 5,134,714 (JANZEN ET AL) 28 JULY 1992	1-26

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

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Date of the actual completion of the international search	Date of mailing of the international search report
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Name and mailing address of the ISA/US	Authorized officer
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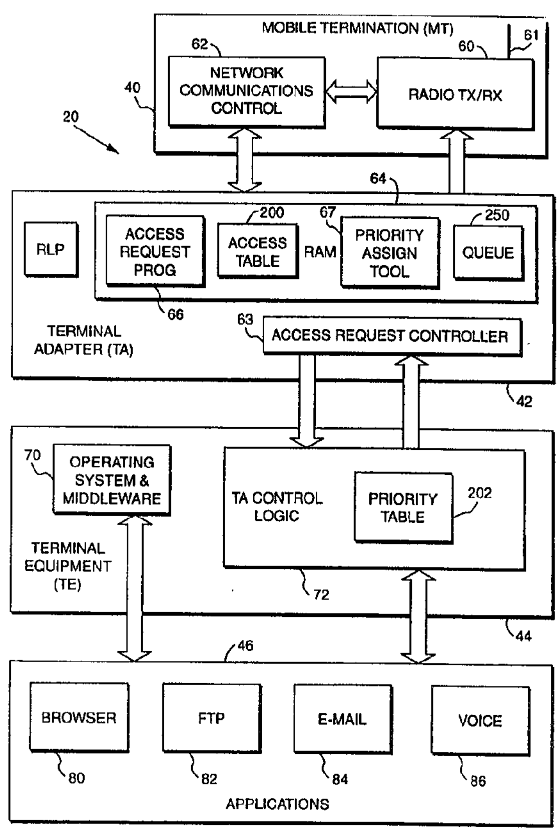
(54) Title: MULTIPLE ACCESS CATEGORIZATION FOR MOBILE STATION

(57) Abstract

A mobile station (20) for radio communications with a telecommunications network (18) has an access request controller (63) which controls whether a mobile termination unit (40) of the mobile station is to transmit access requests and/or data packets to the network from applications (46) correlated with one of plural access classes available to the mobile station. The access request controller has an access request table (200) which contains an access status for each of plural access classes utilizable by the mobile station. The access status for each of the plural access classes is received over the air interface (23) from the network. Each of the plural applications (46) provided at the mobile station is assigned a selectively changeable priority value by the user. The access request controller associates the priority value with one of the plural access classes in the access table (200). The access request controller consults the access table to determine whether an access request or a data packet from an application is to be sent to the network.



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MULTIPLE ACCESS CATEGORIZATION FOR MOBILE STATION

BACKGROUND

1. FIELD OF THE INVENTION

The present invention pertains to telecommunications, and particularly to the provision of multiple types of services for cellular or mobile telecommunications.

2. RELATED ART AND OTHER CONSIDERATIONS

In recent years cellular telephones have become increasingly popular. A cellular telephone is just one example of what is referred to in telephone parlance as a "mobile station" or "mobile terminal". Telecommunications services are provided between a cellular telecommunications network and a mobile station (e.g., cellular telephone) over an air interface, e.g., over radio frequencies. At any moment an active mobile station is communication over the air interface with one or more base stations. The base stations are, in turn, managed by base station controllers (BSCs). The base station controllers are connected via control nodes to a core telecommunications network. Examples of control nodes include a mobile switching center (MSC) node for connecting to connection-oriented, circuit switched networks such as PSTN and/or ISDN, and a general packet radio service (GPRS) node for connecting to packet-switched networks such as Internet, for example.

A mobile station can take on various forms other than a cellular telephone, including a computer (e.g., a laptop computer) with mobile termination capabilities. In some forms, mobile stations are capable of engaging in differing types of services, or multimedia services. In other words, the mobile station can execute several differing types of programs (i.e., "applications") which interact with the user. Examples of these

applications include Internet browsers and electronic mail programs. Several multimedia applications may reside in the same mobile station.

An owner of a mobile station typically enters into a contract or subscription agreement with a service provider (e.g., a company which operates the telecommunications network through which the mobile station engages in telecommunications connections). As part of the subscription agreement, the mobile station is categorized as belonging to one of several access classes available on the network. The particular access class to which a mobile station belongs determines the conditions under which the mobile station will be permitted to use resources of the cellular network. Examples of access classes are provided in GSM 04.08, TIA/EIA IS-136, and IS-95, for example.

In general, when a mobile station needs to access a cellular telecommunications network, the mobile station sends an access request message to the network over the air interface (e.g., the mobile station requests the set up of a "connection"). In the network, either the base station or the base station controller decides whether the mobile station is to be permitted use of a radio resource (e.g., a radio traffic channel) for the requested connection. The permission decision is based primarily upon the access class to which the mobile station belongs. The network may either grant or deny the request, depending on the preference given the mobile station's access class relative to network factors such as network congestion and the like.

As mentioned above, a mobile station may be capable of engaging in several different telecommunications services, and these services may be transacted simultaneously. Different types of telecommunications services may have differing sensitivities for delay. For some types of service, delay in transmissions may not be critical and it may very well be acceptable to wait for several minutes or even hours before the service request is executed. Such is more commonly the case of asynchronous types of services such as electronic mail (E-mail), for example. On the other hand, other types of services are more delay sensitive.

Currently, when a access request for a mobile station is denied by the network, the access requests are repeated by applications executed at mobile station until the

network grants the request. Unfortunately, the repeated access requests undesirably increases radio interference and system load. In a busy cellular communications, a large portion of the radio interference and system load is due to the sending and handling (e.g., denying) of accesses requests.

One technique for curtailing repeated access requests is for the network to broadcast periodically an access status to all mobile stations. In fact, in accordance with this technique the network broadcasts an access status for each of several access classes. Typically the network broadcasts the access status for a number of access classes to the mobile stations. The access status for each access class may be either "granted" or "denied", as appropriate.

Thus, the network has the capability of granting access for some access classes while denying access to other access classes. The access classes thereby form part of a priority mechanism and can be used to regulate the load caused by mobile stations attempting to access the network.

Heretofore each mobile station, or each subscriber identification module (SIM) card in the mobile station, has belonged only to one access class. This can prove a problem when the mobile station is equipped to execute multimedia applications. The multimedia applications may have varying tolerance for congestion and delay, and the one access class to which the mobile station is associated may not be appropriate for all services which can be performed at the mobile station. The inappropriateness is due at least in part to the fact that, as indicated above, some applications have higher tolerance for access delay than other applications.

It is theoretically possible at a mobile station separately to provide one type of subscription (e.g., a SIM module) for each type of application. However, practically this possibility poses problems for the user, such as e.g., the higher costs for multiple subscriptions and increased physical size of the mobile station.

What is needed, therefore, and an object of the present invention, is a mobile station which can be assigned plural access classes, as well as a flexible technique for handling access requests from such a mobile station.

BRIEF SUMMARY OF THE INVENTION

A mobile station for radio communications with a telecommunications network has an access request controller which controls whether a mobile termination unit of the mobile station is to transmit access requests and/or data packets to the network from applications correlated with one of plural access classes available to the mobile station. The access request controller has an access request table which contains an access status for each of plural access classes utilizable by the mobile station. The access status for each of the plural access classes is received over the air interface from the network. Each of the plural applications provided at the mobile station is assigned a selectively changeable priority value by the user. The access request controller associates the priority value with one of the plural access classes in the access table. The access request controller consults the access request table to determine whether an access request or a data packet from an application is to be sent to the network.

A list of access classes stored in the access table can be hardcoded or dynamically changeable either by the network or by the user. In one embodiment, the list of access classes is stored in a memory of a Subscriber Identity Module (SIM).

The access requests issued by the access request controller can include an access request on behalf of an application seeking a circuit-switched service, or an access request on behalf of an application seeking a packet-switched service. In the case of an access request on behalf of an application seeking a packet-switched service, a data packet is marked with its priority value. The access request controller matches the priority value with which the data packet is marked with an access class, and makes a determination based on the access class and the access status for that class whether the packet is to be forwarded to the network or queued.

When an access status for one of the plural access classes changes to an access permitted status, the access request controller waits a timeout period prior to forwarding the access request to the network.

Also provided is a method of operating a mobile telecommunications network wherein an inventive access status message is broadcast. The access status message includes access class status parameters for plural access classes, with each access class

being subdivided into plural subclasses. Differentiation of an access class into subclasses is an alternate way of providing multiple access categorization to a mobile station.

BRIEF DESCRIPTION OF THE DRAWINGS

The foregoing and other objects, features, and advantages of the invention will be apparent from the following more particular description of preferred embodiments as illustrated in the accompanying drawings in which reference characters refer to the same parts throughout the various views. The drawings are not necessarily to scale, emphasis instead being placed upon illustrating the principles of the invention.

Fig. 1 is a schematic view of an example telecommunications network in which the present invention operates.

Fig. 2 is a schematic view showing functional entities of a mobile station according to an embodiment of the invention.

Fig. 2Ais a schematic view showing functional entities of a mobile station according to another embodiment of the invention.

Fig. 3 is a schematic view showing a mapping of functional entities to hardware in a mobile station according to the embodiment of Fig. 2.

Fig. 3A is a schematic view showing a mapping of functional entities to hardware in a mobile station according to the embodiment of Fig. 3.

Fig. 4 is a diagrammatic view of an access table maintained by a mobile station according to an embodiment of the invention.

Fig. 5A is a diagrammatic view of the format of access class status parameters broadcast from a conventional network.

Fig. 5B is a diagrammatic view of the format of access class status parameters broadcast from a network in accordance with a mode of the present invention.

Fig. 6 is a diagrammatic view of the format of a communication priority window through which a user can set priority values relative to plural applications, as well as a priority table affected by such settings.

Fig. 7A is a diagrammatic view showing basic operations performed in a case in which access to a network is sought by an application which employs circuit data.

Fig. 7B is a diagrammatic view showing basic operations performed in a case in which access to a network is sought by an application which employs packet data.

Fig. 8 is diagrammatic view of a terminal adapter (TA) with a timer according to an embodiment of the invention.

Fig. 9 is diagrammatic view a charging function according to an embodiment of the invention.

Fig. 10 is a diagrammatic view of a request including an access class indication according to an embodiment of the invention.

Fig. 11A, Fig. 11B, and Fig. 11C are diagrammatic views of the mobile station of the embodiment of Fig. 2A showing differing modes of changing the contents of an access table stored in a SIM card.

DETAILED DESCRIPTION OF THE DRAWINGS

In the following description, for purposes of explanation and not limitation, specific details are set forth such as particular architectures, interfaces, techniques, etc. in order to provide a thorough understanding of the present invention. However, it will be apparent to those skilled in the art that the present invention may be practiced in other embodiments that depart from these specific details. In other instances, detailed descriptions of well known devices, circuits, and methods are omitted so as not to obscure the description of the present invention with unnecessary detail.

Fig. 1 shows a telecommunications network 18 in which a mobile station 20 communicates with one or more base stations 22 over air interface (e.g., radio interface) 23. Base stations 22 are connected by terrestrial lines to base station controller 24, also known as a radio network controller (RNC). Base station controller 24 is, in turn, connected through a control node known as the mobile switching center 26 to circuit-switched telephone networks represented by cloud 28; and through a GRPS control node 30 to packet-switched telephone networks represented by cloud 32.

As understood by those skilled in the art, when mobile station 20 is participating in a mobile telephonic connection, signaling information and frames of user information from mobile station 20 are transmitted over air interface 23 on designated radio channels to one or more of the base stations 22. The base stations have radio transceivers which transmit and receive radio signals involved in the connection. For information on the uplink from the mobile station 20 toward the other party involved in the connection, the base stations convert the radio-acquired information to digital signals which are forwarded to base station controller 24. Base station controller 24 orchestrates participation of the plural base stations 22 which may be involved in the connection, since mobile station 20 may be geographically moving and handover may be occurring relative to the base stations 22. On the uplink, base station controller 24 picks frames of user information from one or more base stations 22 to yield a coherent connection between mobile station 20 and the other party, whether that party be in PSTN/IDSN 28 or on the Internet 32.

It is the initiation of a connection by mobile station 20 to which the present invention primarily relates. One type of mobile station 20 with which the present invention is particularly useful is a computer with mobile termination, such as a laptop computer, for example. An illustrative embodiment of a suitable mobile station 20 for the present invention is provided in Fig. 2. As shown in Fig. 2, mobile station 20 has the following functional entities pertinent to the present invention: mobile termination entity (MT) 40; terminal adapter (TA) 42; terminal equipment 44; and a set 46 of applications. While each of these entities are described below, it should be understood that the invention is not confined to mobile stations having the same physical separation between functional entities, and that the present invention can be implemented in other than the described functional configuration.

Mobile termination entity (MT) 40, which is sometimes called the Mobile Equipment (ME), contains the radio transmitter/receiver TX/RX 60 (with antenna 61) and communications control 62 toward the network 18, e.g., the setup and release of radio connections, handover, etc. Mobile termination entity (MT) 40 can be a standard mobile pocket telephone (e.g., a GSM phone) or a phone card within mobile station 20.

Terminal adapter (TA) 42 acts as an adaptation between mobile termination entity (MT) 40 and the applications in the set 46 of applications. The terminal adapter (TA) 42 is typically realized as a Modem implemented on a PCMCIA (Personal Computer Memory Card International Association) card, which is inserted in a slot of terminal equipment 44. The terminal adapted (TA) 42 has a CPU 63 as well as a RAM 64 and a MT interface (I/F) 65. CPU 63 serves as an access request controller when executing an access request program 66 stored in RAM 64. As explained hereinafter, access request controller 63 of terminal adapter (TA) 42 selectively forwards call requests or data packets in accordance with access class status parameters received from network 18.

Terminal equipment 44 is normally a small computer (or computer platform), and as such includes both hardware and software. Terminal equipment 44 thus has typical aspects of a computer platform, e.g., a processor an operating system and middleware (Internet protocol suits, for example), collectively illustrated by reference numeral 70 in Fig. 2. In addition, terminal equipment 44 has control logic 72 (executed by the processor) for controlling terminal adapter (TA) 42. Control logic 72 performs set-up and release of calls to and from the network 18.

As shown in Fig. 2, the set 46 of applications illustrated for the example embodiment includes an Internet browser 80; a file transfer program (FTP) 82; an E-mail program 84; and voice service 86. Each application is normally a program which is executed by the processor of terminal equipment 44 and which interacts with the user via, e.g., data input devices such as a keyboard and/or mouse and output or display devices. These applications typically can run on any personal computer (with or without radio access). The applications in set 46 use a number of application programming interfaces (APIs) towards the terminal equipment 44. One or several of these APIs is for communications with the network 18. Examples of APIs are Unix

BSD Socket, WinSock or more telcom-specific APIs such as the Microsoft Intel Telephony API, AT&T, and Novell TSAPI or OnTheMove Mobile API. Thus, although the set 46 of applications is represented in Fig. 2 as an entity separate from terminal equipment 44, it should be understood that the set 46 of applications executed on the terminal equipment 44 if the terminal equipment 44 is a general computer, with the applications that are executed using the APIs offered by terminal equipment 44.

Fig. 3 shows how the functional entities of mobile station as illustrated in Fig. 2 are mapped onto hardware components of mobile station 20. In essence, Fig. 3 shows terminal equipment 44 wherein mobile termination entity (MT) 40 and terminal adapter (TA) 42 are cards situated in card slots. Terminal adapter (TA) 42 is connected to central processing unit (CPU) 100 by bus 102. Mobile termination entity (MT) is connected to MT interface 65 of terminal adapter (TA) 42 by a cable.

Memories of terminal equipment 44, particularly read only memory (ROM) 104 and random access memory (RAM) 106 are also connected to central processing unit (CPU) 100 by bus 102. In RAM 106 are stored the TA control logic 72, the set 46 of applications, and TCP/IP stack 108.

Terminal equipment 44 interfaces with a user through input device(s) 110 and output device(s) 112, each connected through respective appropriate interfaces 120 and 122 to bus 102. Input device(s) 110 can be a keyboard and/or mouse, for example, while output device(s) 112 can take the form of a display device, such as a LCD display panel, for example.

As indicated above, a subscription agreement exists for each mobile station 20. One pertinent term of the subscription agreement pertinent is the access class in which the mobile station is categorized. As explained previously, heretofore the subscription agreement for a mobile station assigned the mobile station to one and only one of several possible access classes. In accordance with an embodiment of the present invention, on the other hand, the subscription agreement for mobile station 20 permits mobile station 20 to participate in plural access classes. Since mobile station 20 has multimedia services as evidenced by the set 46 of applications executable thereon (see Fig. 2), participation by mobile station 20 in plural access classes affords the user an

opportunity to have its separate services seek access to network 18 using differing access criteria.

The subscription agreement terms are stored in an access table 200. Access table 200 is in RAM 64 of terminal adapter (TA) 42. An example access table 200X for one mode of the invention is shown in Fig. 4, which includes (in the left column thereof) a listing of each access type to which mobile station 20 can participate according to the subscription agreement. In particular, in the mode of Fig. 4 the applications in set 46 which are executed by mobile station 20 can be afforded one of access class C04, access class C09, or access class C14. How each application in set 46 is associated with one of the plural access classes available in accordance with the subscription agreement is described below in connection with a priority table 202 maintained by TA control logic 72.

Fig. 4 also shows, in the right hand column of access table 200, the status of each of the plural access classes as determined from network 18. At the moment in time shown in Fig. 4, the network precludes access classes C09 and C14 from requesting access to the network, while access class C04 is permitted access.

The base station controllers 24 of network 18 periodically broadcast access class status parameters over air interface 23. One example of the broadcasting of such access class status parameters occurs in the European GSM system wherein the access class status parameters take the form of RACH control parameters which are transmitted on the RACH channel. Fig. 5A shows a format of an information element containing the RACH control parameters, wherein octets 3 and 4 carry the access status bits for each of sixteen access classes (AC) C00 through C15.

Mobile termination entity (MT) 40 detects the access class status parameters (RACH control parameters) as these parameters are periodically or otherwise repetitively broadcast over air interface 23. The detected access class status parameters are sent to terminal adapter (TA) 42. As the access status for one or more of the access classes changes over time, terminal adapter (TA) 42 updates the status of the access classes which are pertinent for the subscription agreement of mobile station 20. For example, with reference to the mode shown in Fig. 4, for example, if the access status of

access class C09 were to change from "denied" to "permitted", terminal adapter (TA) 42 would note such change and accordingly update the "access status" column of access table 200X.

The fact that mobile station 20 has plural access classes available in accordance with its subscription agreement allows the user of mobile station 20 to differentiate on an access priority basis between the applications included in the set 46 of applications. In this regard, the user can execute a priority assignment program 210 (stored in RAM 106 [see Fig. 2]) for the purpose of assigning a priority to each of the applications in the set 46 of applications.

Fig. 6 is a diagrammatic view of a particular window, known as the priority assignment window 220, which is displayed on output device 112 during execution of priority assignment tool or program 210. The priority assignment tool 210 is preferably stored in RAM 64 of terminal adapter (TA) 42, but is executed by the terminal equipment 44. Alternatively, priority assignment tool 210 can be stored in the memory of terminal equipment 44 and executed by terminal equipment 44. The priority assignment tool 210 is aware of the fact that support for the priorities exists in terminal adapter (TA) 42 and in mobile station 20.

As is apparent from the priority assignment window 220, the user has already entered the network-related applications from the set 46 of applications into window 220. In particular, window 220 as seen in Fig. 2 already has the applications listed for "Web Browsing" (corresponding to browser application 80); an "E-mail" (corresponding to E-mail application 84); "File Transfer" (corresponding to FTP application 82); and "Voice" (corresponding to voice series 86). Moreover, in the "Priority" dialogue boxes which correspond to each application, the user has entered a default priority value. As is apparent by the priority values displayed in window 220, a lower numerical value indicates a higher priority. In this regard, "Web Browsing" (corresponding to browser application 80) and "File Transfer" (corresponding to FTP application 82) have both been assigned a relatively low priority("4") by the user, whereas the "E-mail" application has been assigned a medium priority ("3") and "speech" (corresponding to voice application 86) as been assigned a high priority ("2"). The default priority can be overridden by the user e.g., by selecting an icon or button

indicative of an "urgent mode" while in the application itself. This temporary change of priority must be supported by the application in some way, e.g., by having an "urgent" button in a graphical interface of an E-mail program, for example.

As the user makes or changes priority assignments via priority assignment window 220 during execution of priority assignment program 210, the priority table 202 is likewise updated as also reflected in Fig. 6. When priority table 202 is initialized or updated, TA control logic 72 sends the contents of priority table 202 to terminal adapter (TA) 42. Access request controller 63 of terminal adapter (TA) 42 makes an association between each of the priorities assigned by the user (e.g., in priority assignment window 220) with one of the access classes permitted by the subscription agreement (e.g., in the example of Fig. 4, one of access classes C04, C09, or C14). Access request controller 63 is also involved, as hereinafter explained, in determining when an access request from one of the applications in the set 46 of applications can make an access request to the network 18.

At this point it should be kept in mind that some of the applications in the set 46 of applications may involve packet data, while others of the applications may involve circuit data. Although generally the same in principle regarding the present invention, the cases of packet data and circuit data are separately discussed and illustrated.

The case of seeking access by an application which employs circuit data is shown in Fig. 7A. Operation 7A-1 reflects the repeated broadcast of access class status parameters (RACH control parameters) by the network 18. Upon reception of the access class status parameters by mobile termination entity (MT) 40, the access class status parameters are forwarded to terminal adapter (TA) 42 as indicated by operation 7A-2. As shown by operation 7A-3, access request controller 63 of terminal adapter (TA) 42 updates its access table 200 (see Fig. 4 for an example) using the access class status parameters.

Fig. 7A next shows, as operation 7A-4, a circuit data-based application (e.g. voice application 86) seeking access to network 18 by way of a call request. The call request of operation 7A-4 is handled by TA control logic 72, which (as indicated by operation 7A-5) notes from priority table 202 the particular priority presently assigned

to the requesting application. For example, in the case of the circuit data-based application being speech, TA control logic 72 would associate a priority value of "2" with the call request. TA control logic 72 then forwards the call request plus the priority value to access request controller 63 of terminal adapter (TA) 42 as indicated by operation 7A-6.

At operation 7A-7 the access request controller 63 of terminal adapter (TA) 42 maps the priority value received from the call request to one of the plural access classes permitted to mobile station 20 under the subscription agreement. Access request controller 63 has a mapping function that relates the priority values of priority table 202 to the access classes of access table 200. Using the illustration of Fig. 4 and the priority assignments shown in Fig. 6, an example mapping performed by access request controller 63 could be as follows: high priority (e.g., "2") is mapped to access class C04; medium priority (e.g., "3") is mapped to access class C09; and low priority (e.g., "4") is mapped to access class C14.

The priority/access class mapping of operation 7A-7, which results in association of an access class with the call request, at operation 7A-8 the access request controller 63 determines from access table 200 whether network access is presently permitted for the access class now associated with the application making the request. For example, if the access class associated with the requesting application were access class C02, at the time shown in Fig. 4 it would be realized by terminal adapter (TA) 42 that the network 18 is presently permitting access. In such case, access request controller 63 would forward a connection request (operation 7A-9) to mobile termination entity (MT) 40, which thereafter would communicate with the network 18 in conventional fashion (indicated by operation 7A-10) for setting up the connection with the requesting applications program.

On the other hand, if the access status associated with the requesting applications program has a "denied" status as discerned by access request controller 63 from access table 200, the access request controller 63 via terminal equipment 44 would so advise the requesting applications program. In the access denial scenario, the requesting application can be advised to reattempt the access at a later date. Alternatively, the requesting applications program may be put on hold for a predetermined period of time

while access request controller 63 waits to ascertain whether the access status for the associated access class happens to change during the predetermined wait or hold period.

In the example of Fig. 7A, it should be understood that the access class status parameters are repetitively transmitted from the network 18 to mobile station 20, and that the operations 7A-1 through 7A-3 can be performed at differing times. In fact, an instance of operations 7A-1 through 7A-3 could be performed at the time of or just before the call request with priority value is sent to access request controller 63, e.g., the time of operation 7A-6, for example.

The case of seeking access by an application which employs packet data but which does not use a call setup phase is shown in Fig. 7B. A packet data call may include a call setup phase, which is similar to the setup of a circuit data connection as above described. The difference is the data transfer phase which is described below, where a second level of access load control is accomplished.

In the case of an application which employs packet data but which does not use a call setup phase, the mobile termination entity (MT) 40 of mobile station 20 routinely receives the access class status parameters broadcast from the network 18, in the manner aforedescribed. Operations 7B-1 through 7B-3 correspond to operations 7A-1 through 7A-3 previously described for the respective reception of the access class status parameters, transmission thereof to access request controller 63 [operation 7B-2], and updating of the priority table 202 (operation 7B-3).

Operation 7B-4 occurs as one of the applications in the set 46 of applications seeks, via TCP/IP 106, to send a data packet (e.g., an Internet packet) to the network 18. Initially the data packet is sent to a "Prioritizer", e.g., to TA control logic 72. As shown by operation 7B-5, the "Prioritizer" checks the priority table 202 and associates a priority value with the particular application which desires to send the data packet, and thus associates the priority value with the data packet itself. The association of priority value with the data packet (based on the application program seeking to send the data packet) is understood with reference to Fig. 6 as discussed above. Thus, the "Prioritizer" essentially "marks" the data packet with a priority value.

As shown by operation 7B-6, the data packet with its associated priority is forwarded by TA control logic 72 to access request controller 63. Operation 7B-7 shows terminal adapter (TA) 42 queuing the data packet in a packet queue 250 for transfer to the network 18. Packet queue 250 can reside in RAM 64 of terminal adapter (TA) 42. When the marked data packet comes to the head of queue 250, as indicated by operation 7B-8 the access request controller 63 maps the priority value with which the data packet is marked to one of the access classes designated in the subscription agreement for base stations 22. The mapping of operation 7B-8 is essentially the same as that of operation 7A-7, with the exception that the mapping is for a data packet rather than a call request. At operation 7B-9 the access request controller 63 determines from access table 200 whether network access is presently permitted for the access class now associated with the data packet at the top of queue 250.

If the access table 200 indicates that the access status for the access class associated with data packet is a "denied" status, access request controller 63 maintains the data packet in queue 250 for a predetermined period of time. If, within that predetermined period of time, the access status for the access class of the data packet changes to a "permitted" status, the data packet is taken from the head of queue 250 and passed to mobile termination entity (MT) 40 for transmission to the network 18.

Should it ever occur that queue 250 gets overloaded with data packets, lower-prioritized packets in queue 250 are discarded. The TCP/IP protocol 106 has a control mechanism which handles any extra delay caused by overload of queue 250. It should be understood that queue 250 can represent plural buffers. Moreover, some or all of the buffering provided by queue 250 can be distributed to RAM 106 of terminal equipment 44 if desired.

When the access table 200 indicates that the access status for the access class associated with the data packet is "permitted", the data packet is sent from access request controller 63 of terminal adapter (TA) 42 to mobile termination entity (MT) 40 as indicated by operation 7B-10 in Fig. 7B. In usual fashion, mobile termination entity (MT) 40 then sends a request for a channel (operation 7B-11). In response, a channel assignment is received from network 18 . The mobile termination entity (MT) 40 is then able to send the data packet over the assigned channel. After transmission of the

data packet to network 18, the network 18 sends an acknowledgment which is forwarded to terminal adapter (TA) 42.

Now that access request has been described, both with reference to circuit data (Fig. 17A) and packet data (Fig. 17B), an example is now provided wherein it is desirable to change the priority value assigned to one of the applications in the set 46 of applications. At the time shown in Fig. 6, the window 220 indicates that the file transfer program (FTP) 82 has a low priority (i.e., a priority value of "4"). File transfer typically may not be a very urgent matter, so that if the network 18 is congested it is of little consequence that transfer of the file may be postponed. On the other hand, if the user is about to board an aircraft (in which operation of the mobile station is not permitted) and there is a need to transfer a file to an eager recipient, the present invention permits the file transfer program (FTP) to use temporarily a higher priority value (e.g., a higher access class). To do so, with the input device 110 (e.g., a mouse) the user changes the priority value in the dialogue box for the file transfer program (FTP) to obtain a lower number (it being remembered that lower numbers correspond to higher priority values). Thus, using the higher priority value, the user would be able to send the necessary files despite network congestion which otherwise might have precluded file transfer at the original priority value assigned to the file transfer program (FTP).

As mentioned above, the contents of access table 200 is established in accordance with the subscription agreement between the operator of the network 18 and the user (e.g., owner) of mobile station 20. In one embodiment of the invention, the subscription-determined contents of access table 200 is hardcoded in the memory of terminal adapter (TA) 42. In this embodiment, the access classes in which mobile station 20 can participate will always be the same access classes as initially established and hardcoded into access table 200.

In other embodiments of the invention, the terms of the subscription agreement for mobile station 20 can change so that mobile station 20 can be usable with other access classes. For example, the user or subscriber can contact the network operator and request a change of terms regarding the subscription agreement, e.g., negotiate new terms for the subscription agreement. In such case, the contents of access table 200 can be changed to reflect the re-negotiated terms (e.g., new access classes). In particular,

the network operator can download through the network 18 a new access table 200 to replace the prior access table 200. In this manner, the subscriber can update or otherwise modify the access table 200 in accordance with changed terms of the subscription agreement. Alternatively, the user or subscriber can himself modify the contents of access table 200. The user-implemented modification of access table 200 can be accomplished, if desired, by a special function of priority assignment program 210. Of course, any change of subscription agreement terms such as a change of available access classes can trigger new or additional charges when new access classes are utilized. Moreover, the mere ability for the user to change access classes at the user's initiative incur a greater subscription fee or be a chargeable event.

Another illustrative embodiment of a suitable mobile station 20A for the present invention is provided in Fig. 2A and Fig. 3A.. As shown in Fig. 2A, mobile station 20A has the same basic type of functional entities as the mobile station 20A. However, the mobile station 20A of the embodiment of Fig. 2A and Fig. 3A has a Subscriber Identity Module (SIM) 260 [also know as a SIM card] included in mobile termination entity (MT) 40. Subscriber Identity Module (SIM) 260 has its own CPU 262 and memory (RAM) 264. Through appropriate interface(s), Subscriber Identity Module (SIM) 260 is connected to the network communications control 62 of mobile termination entity (MT) 40, as well as to terminal equipment 44.

Rather than having an access table stored in terminal equipment 44 as in the embodiment of Fig. 2 and Fig. 3, the mobile station 20A of the embodiment of Fig. 2A and Fig. 3A has access table 200SIM stored in memory 264 of Subscriber Identity Module (SIM) 260. Thus, for mobile station 20A, the conditions or terms of the mobile subscription agreement (e.g., access classes) are stored in access table 200SIM of Subscriber Identity Module (SIM) 260.

Upon startup, terminal equipment 44 can read the list of access classes from access table 200SIM of Subscriber Identity Module (SIM) 260. As the access request controller 63 executes the access request program 66, the access class values stored in access table 200SIM are utilized in connection with the performance of operations such as those discussed with reference to the embodiment of Fig. 2 and Fig. 3.

Moreover, in the event that the Subscriber Identity Module (SIM) 260 has satisfactory capacity and processing, the CPU 262 of Subscriber Identity Module (SIM) 260 can serve, at least in part, as the access request controller 63. In this regard, some or all of access request program 66 can be stored in memory 264 of Subscriber Identity Module (SIM) 260.

There are several ways of changing the conditions or terms (e.g., access classes) for the SIM card-containing mobile station 20A. A first way of changing access classes, as shown in Fig. 11A, is to replace a first Subscriber Identity Module (SIM) 260(1) [having a first set of access classes] with a second Subscriber Identity Module (SIM) 260(2) [having a second set of access classes]. A second way of changing access classes (shown in Fig. 11B) is to remove the original Subscriber Identity Module (SIM) 260 contained in the mobile station 20A and take the Subscriber Identity Module (SIM) 260 to a programming device 1100. In this second way, the access table 200SIM of the Subscriber Identity Module (SIM) 260 is reprogrammed with updated or revised access class information, so that the original but reprogrammed Subscriber Identity Module (SIM) 260' can be returned to mobile station 20A. A third way (shown in Fig. 11C) of changing access classes stored in access table 200SIM of Subscriber Identity Module (SIM) 260 is for the network (at the behest of e.g., the service provider) to send a special access table message ("AT MESSAGE") to mobile station 20A, the access table message serving to down load the contents of a replacement access table into access table 200SIM.

In its various embodiments the invention thus permits mobile station 20 to participate in plural access classes. In this regard, it should be realized that the invention extends to a situation in which a network provides access classes, with one or more access classes having access subclasses. In such a situation, it should be understood that in the present invention the mobile station 20 can participate in more than one access class, or can participate in plural access subclasses for one or more than one access class.

In the above regard, the network 18 can send out a message similar to that containing the RACH control parameters as pictured in Fig. 5A, but having subclass values for each of the access classes. An example of such a message is illustrated in

Fig. 5B. The network message of Fig. 5B has access status for sixteen access classes, and more particularly for four subclasses for each of the sixteen subclasses. The network message of Fig. 5B has eight octets. The first four bits a1, a2, a3, and a4 of the first octet carry access status for each of the four corresponding subclasses of the first access class. The last four bits b1, b2, b3, and b4 of the second octet carry access status for each of the four corresponding subclasses of the second access class. In similar manner, each of the remaining seven octets carry access status bits for the subclasses of two access classes: the second octet for the third and fourth access classes, the third octet for the fifth and sixth access classes, and so forth.

The person skilled in the art knows how to format a network message such as the RACH control parameter message of Fig. 5A, and how to broadcast the same over the air interface 23. Now that it is realized by the present invention that an access subclass scheme is also possible, the person skilled in the art is able to implement the change in format of the network message of Fig. 5B and to transmit the same.

With the subclass-based network message of Fig. 5B, it is possible to assign an access class to a mobile station in its subscription agreement, but also to allow the mobile station to participate in plural subclasses of the assigned access class. In a more complex arrangement, the mobile station may participate in access subclasses of plural access classes, if desired.

Thus, in view of the foregoing, the term "access class" as used herein is understood to refer to any type of access categorization, including the access subclass scenario described above. Advantageously, the present invention enables mobile station 20 to participate in plural access categorizations, e.g., plural access classes or plural access subclasses.

It should be recognized that mobile stations are capable of handling more than one simultaneous call and more than one simultaneous connection. In other words, more than one applications program may simultaneously be involved with a connection to network 18. Moreover, several of these calls from the applications program may use the same connection (e.g., the same radio channels over the air interface 23, for example). When services are simultaneously used, the terminal adapter (TA) 42 may choose either (1) to

use a radio connection already in use by an existing call or (2) to setup a new radio connection. If an already existing radio connection was used by a call with lower priority, then a new connection may not be necessary.

In the embodiments described herein, the priority value assigned by the user to the applications in the set 46 of applications has a relationship to, but is not necessarily the same as, access class. It should be understood that for sake of simplification, for example, the priority value and access class may be the same. That is, in setting priority values in window 220 of Fig. 6, the numbers selected by the user may actually be access class numbers.

The moment that an access status changes from "denied" to "granted" for a particular access class, there yet may be a tendency for the network to overload with a burst of access requests. Another embodiment of the terminal adapter (TA), shown as terminal adapter (TA) 842 in Fig. 8A, has a timer 860 which attempts to ameliorate this problem. Timer 860 has a time value stored therein. When the access status changes for an access class involved in mobile station's subscription agreement, terminal adapter (TA) 842 waits for a timeout corresponding to the value in timer 860 before forwarding the call request or data packet to mobile termination entity (MT) 40.

The time value stored in timer 860 can be, for example, a random number computed by mobile station 20. In this way, numerous access requests from many mobiles waiting for access can be linearly distributed (e.g., between O and Y milliseconds), relieving the load on the network. The value of Y is set by the network operator, or is a fixed value.

Employment of the timeout value smoothes the burst of access requests from the mobile stations. Alternatively, the timer can be located in mobile termination entity (MT) 40, and started by terminal adapter (TA) 842 when the change of access status is detected. It should also be understood that the timer 860 and timeout prior to sending an access request is not confined to embodiments wherein the mobile station participates in plural access classes, but that the timeout principle also applies to the traditional mobile station having only one access class.

As mentioned above, the user or subscriber can be charged different rates for connections of differing priorities. When a user assigns to an application program a priority level that is more likely to have a denied access status (likely for an application that has higher tolerance for delay), the user is not billed as much for the connection as if the user had selected a more favorable priority for a less restricted access class.

Fig. 9 shows mobile station sending a "request" 900 (which can be either an access request or channel request according to whether the service is for circuit-switched or packet-switched data) to network. At least some of the contents of the request 900 is ultimately routed (e.g. by diversity handling at a base station controller 24) to a control node CN. Control node CN can be a MSC for circuit-switched data or a GPRS control node for packet-switched data. As shown in Fig. 9, control node includes a service switching part SSP, a service control part SCP, and a database CNDB.

As shown in Fig. 10, the request 900 includes an access class indicator ACI. For the access class scheme of Fig. 5A, the access class indicator ACI can be four bits in length, since the sixteen access courses of the Fig. 5A scheme are representable by four bits. For the access class scheme of Fig. 5B (which has access subclasses), the access class indicator ACI can be six bits in length, with four bits utilized to express the access class and two bits utilized to express the particular subclass of the expressed access class.

The database (CNDB) of control node CN has a record 910 for each subscriber. The record indicates the access classes (and access subclasses where applicable) permitted for use by the subscriber in accordance with the terms of the subscriber's subscription agreement. For example, record 910 has fields PAC1...PACn reflecting permitted access classes 1-n for the subscriber.

When request 900 is received at control node CN, the request 900 is sent by the SSP to the service control part SCP, as indicated by event 9-1. Using the access class indicator ACI contained in request 900, as evidenced by event 9-2, the SCP checks the subscriber's record in database CNDB to ensure that the access class indicator ACI of the request 900 is in one of the permitted access class (PAC) fields of record 910. If not, the request is denied. If the check is positive, the request is granted and service control part SCP performs a charging function for the call. In this regard, service control part

determines the current rate for the particular access class indicated by the access class indicator ACI, and based on other factors such duration of call or number of packets, etc. determines a financial charge for the call. As indicated above, an access class which has a low probability for having access status denied can be charged at a higher rate.

One specific non-limiting example of a particular type of network 18 (see Fig. 1) with which the present invention can be employed is a code division multiple access (CDMA) mobile telecommunications system. In a CDMA system, the information transmitted between each base station 22_1 through 22_n and the mobile station is modulated by a different mathematical code (such as a spreading code) to distinguish it from information for other mobile stations which are utilizing the same radio frequency. Thus, in CDMA, the individual radio links are discriminated on the basis of codes. In addition, in CDMA mobile communications, typically the same baseband signal with suitable spreading is sent from several base stations (e.g., base stations 22_1 through 22_n) with overlapping coverage. The mobile station can thus receive and use signals from several base stations simultaneously. Moreover, since the radio environment changes rapidly, a mobile station likely has radio channels to several base stations at the same moment, e.g., so that the mobile station can select the best channel and, if necessary, use signals directed to the mobile from various base stations in order to keep radio interference low and capacity high. This utilization of radio channels from multiple base stations by a mobile station in a CDMA scheme is termed "soft handover." Additional details of diversity and soft handover are provided e.g., by United States Patent Application Serial Number (attorney docket 2380-3) filed November 26, 1997, entitled "Multistage Diversity Handling for CDMA Mobile Telecommunications", and United States Patent Application Serial Number (attorney docket 2380-4) filed November 26, 1997, entitled "Diversity Handling Moveover for CDMA Mobile Telecommunications", both of which are incorporated herein by reference.

In the example illustrated embodiment, base stations 22, base station controller 24, mobile switching center (MSC) 26, and GPRS control node 30 are each ATM-based nodes. As such, each of these nodes has an ATM switch. It should be understood, however, that the present invention is not confined to ATM packets or to employment of ATM switches.

It should be understood that, unless specifically stated to the contrary, reference to any mobile station herein expressly includes mobile station 20A of the embodiment of Fig. 2A and Fig. 3A. In fact, the teachings of the invention are applicable to all embodiments herein disclosed. For example, the teachings of Fig. 8 and Fig. 9 are equally applicable to the embodiment of Fig. 2A and Fig. 3A as to the embodiment of Fig. 2 and Fig. 3.

The present invention allows a mobile station to have multiple access classes without increasing cost or size of the mobile station itself. Having the benefit of plural access classes, at a peak traffic hour the mobile station can move some of its traffic to a lower priority, and hence possibly to another time, thereby better utilizing resources of the network. Moreover, the present invention facilitates an orderly placement of access requests in accordance with a prioritized order after network congestion diminishes. Further, as explained in connection with Fig. 9, for example, the network operator can charge for different delay requirements while yet maintaining just one subscription per user.

While the invention has been described in connection with what is presently considered to be the most practical and preferred embodiment, it is to be understood that the invention is not to be limited to the disclosed embodiment, but on the contrary, is intended to cover various modifications and equivalent arrangements included within the spirit and scope of the appended claims.

WHAT IS CLAIMED IS:

1. A mobile station for radio communications with a telecommunications network, the mobile station comprising:

a mobile termination unit which handles radio communications over an air interface with the network;

an access request controller which controls whether the mobile termination unit is to transmit one of (1) an access requests, and (2) data packets, for each of plural access classes of the network.

2. The apparatus of claim 1, wherein the access request controller has an access request table which contains an access status for each of plural access classes utilizable by the mobile station, and wherein the access request controller consults the access request table to determine whether one of (1) an access request, and (2) data packet is to be sent to the network for a selected one of plural services provided at the mobile station.

3. The apparatus of claim 1, wherein the access status for each of the plural access classes is received over the air interface from the network.

4. The apparatus of claim 1, further comprising plural applications executable at the mobile station, and wherein each of the applications is assigned a priority value, and wherein the priority value correlates to one of the plural access classes.

5. The apparatus of claim 4, wherein the priority value assigned to each of the applications is changeable by the user.

6. The apparatus of claim 3, wherein a list of access classes available to the mobile station is hardcoded in a memory of the mobile station.

7. The apparatus of claim 3, wherein a list of access classes available to the mobile station is stored in a memory of the mobile station, and wherein a user of the mobile station can change contents of the list.

8. The apparatus of claim 1, wherein a list of access classes available to the mobile station is stored in a memory of a SIM card of the mobile station.

9. The apparatus of claim 8, wherein the memory is reprogrammable for changing the list of access classes..

10. The apparatus of claim 8, wherein the list of access classes is changeable by an access table message transmitted by the telecommunications network.

11. The apparatus of claim 1, wherein the access requests transmitted by the access request controller is on behalf of an application seeking a circuit-switched connection.

12. The apparatus of claim 1, wherein the data packet transmitted by the access request controller is on behalf of an application seeking a packet-switched service.

13. The apparatus of claim 1, wherein when an access status for one of the plural access classes changes to an access permitted status, the access request controller waits a timeout period prior to forwarding one of (1) the access request and (2) the data packet to the network.

14. The apparatus of claim 1, wherein the access request controller is situated (1) a terminal adapter and (2) terminal equipment.

15. A mobile station for radio communications with a telecommunications network, the mobile station comprising:

a mobile termination unit which handles radio communications with the network;

an access request controller;

terminal equipment connected to the mobile terminal unit;

plural applications executable on the terminal equipment;

wherein, at the access request controller, each of the plural applications is associated with one of plural access classes allotted to the mobile station,

wherein, for each of the plural access classes available to the mobile station, the access request controller stores an access status as received from the network; and

wherein, when one of the applications requires access to the network, the access request controller determines whether to send one of (1) an access request and (2) a data packet to the network in accordance with the stored access status of the associated access class.

16. The apparatus of claim 15, wherein each of the plural applications is associated with one of plural access classes by a priority value, the apparatus further comprising a memory wherein is stored an application/priority table in which each of the plural multimedia applications is assigned a priority value, and wherein the access request controller associates the priority value with an access class.

17. The apparatus of claim 16, wherein the priority value assigned to each of the applications is changeable by the user.

18. The apparatus of claim 15, wherein a list of access classes available to the mobile station is hardcoded in a memory of the mobile station.

19. The apparatus of claim 15, wherein a list of access classes available to the mobile station is stored in a memory of the mobile station, and wherein a user of the mobile station can change contents of the list.

20. The apparatus of claim 15, wherein a list of access classes available to the mobile station is stored in a memory of a SIM card of the mobile station.

21. The apparatus of claim 20, wherein the memory is reprogrammable for changing the list of access classes.

22. The apparatus of claim 20, wherein the list of access classes is changeable by an access table message transmitted by the telecommunications network.

23. The apparatus of claim 15, wherein the access requests sent by the access request controller are on behalf of an application seeking a circuit-switched connection.

24. The apparatus of claim 15, wherein the data packets sent by the access request controller are on behalf of an application seeking a packet-switched service.

25. The apparatus of claim 15, wherein when an access status for one of the plural access classes changes to an access permitted status, the access request controller waits a timeout period prior to forwarding one of (1) the access request and (2) the data packet to the network.

26. The apparatus of claim 15, wherein the access request controller is situated in one of (1) a terminal adapter and (2) terminal equipment.

27. Method of operating a mobile station in radio communications with a telecommunications network, the method comprising:

(1) providing plural service applications at the mobile station; and

(2) associating one of plural access classes available to the mobile station with an application desiring to make a transmission of one of (1) an access request and (2) a data packet;

(3) determining, on the basis of the access class associated with the application, whether the desired transmission of step (2) is to be forwarded to the network..

28. The method of claim 27, further comprising receiving a set of access class status parameters available to the mobile station over an air interface with the network.

29. The method of claim 27, further comprising:

assigning a priority value to the application; and

when the application desires to make an access request, associating the priority value with one of the plural access classes available to the mobile station.

30. The method of claim 28, further comprising selectively changing the priority value assigned to the application.

31. The method of claim 27, wherein the determination of step (3) is performed by consulting an access table which contains an access status for each of plural access classes available to the mobile station.

32. The method of claim 31, further comprising receiving the access status for each of the plural access classes over the air interface from the network.

33. The method of claim 27, further comprising hardcoding in the access table a list of access classes available to the mobile station.

34. The method of claim 31, further comprising permitting the user to change a list of access classes in the access table.

35. The method of claim 31, further comprising:

storing in a memory of a SIM card of the mobile station a list of access classes available to the mobile station; and

using the list of access classes as the plural access classes of step (2).

36. The method of claim 35, further comprising reprogramming the memory to update the list of access classes.

37. The method of claim 35, further comprising changing the list of access classes in accordance with an access table message transmitted by the telecommunications network.

38. The method of claim 27, wherein the access requests issued by the access request controller includes an access request on behalf of an application seeking a circuit-switched connection.

39. The method of claim 27, wherein the access requests issued by the access request controller include an access request on behalf of an application seeking a packet-switched connection.

40. The method of claim 27, further comprising waiting a predetermined timeout period prior to forwarding the transmission of step (2) to the network.40. Method of operating a mobile telecommunications network having access classes, the method comprising:

broadcasting a message including access class status parameters having access status information for plural access classes to a mobile station;

including in the message access status information for at least one of plural access subclasses for at least one of the plural access classes.

41. The method of claim 41, wherein the message has a bit associated with each of the plural access subclasses.

42. A computer program product having instructions stored in a memory and executable on a processor for associating an application resident at a mobile station with one of plural access classes of a telecommunications network available to the mobile station.

43. The product of claim 43, further comprising consulting an access request table which contains an access status for each of the plural access classes utilizable by the mobile station to determine whether one of (1) an access request, and (2) data packet is to be sent to the network.

Fig. 1

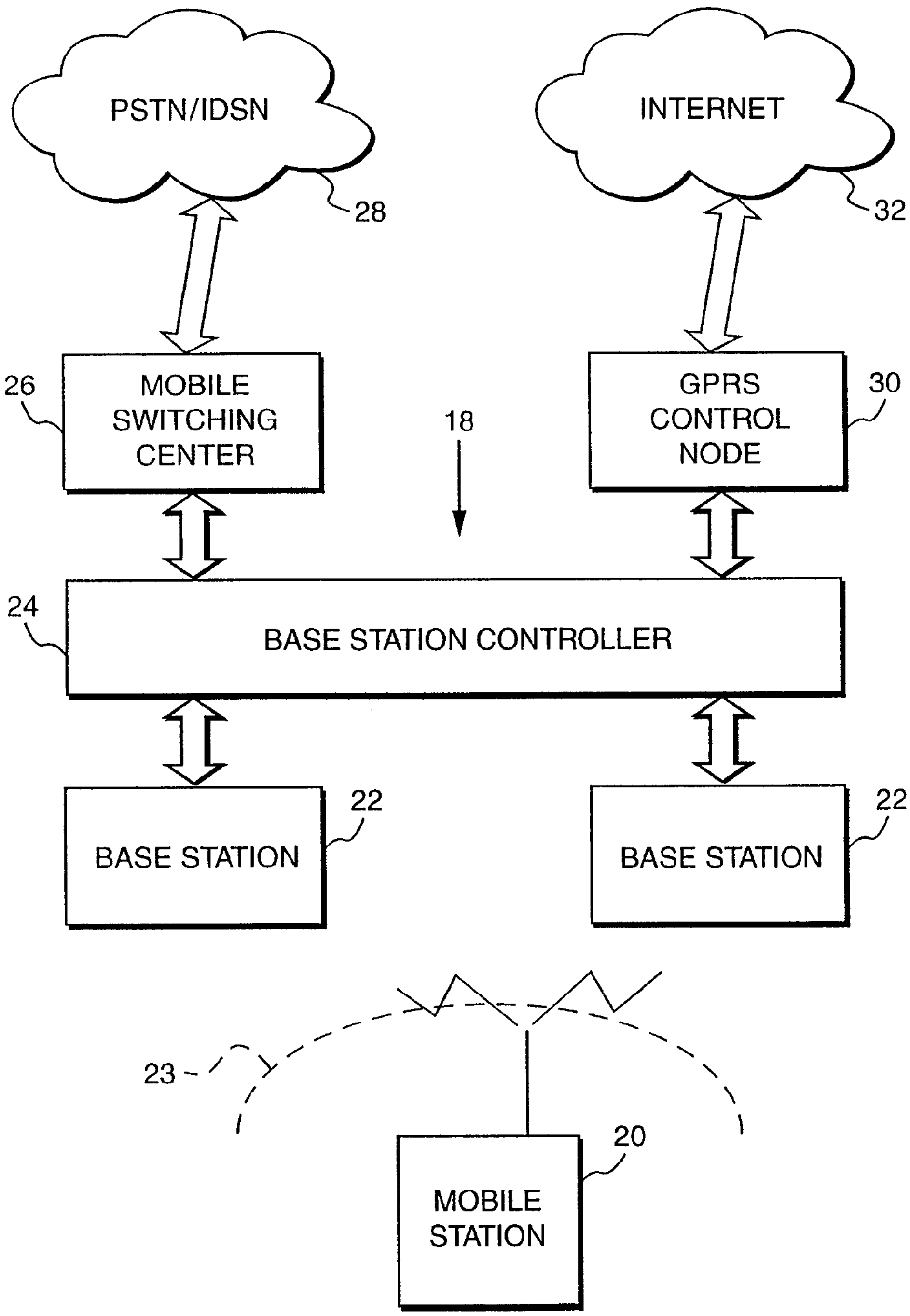

PSTN/IDSN
28
INTERNET
32
26
MOBILE SWITCHING CENTER
18
GPRS CONTROL NODE
30
24
BASE STATION CONTROLLER
BASE STATION
22
BASE STATION
22
23
20
MOBILE STATION

Fig. 2

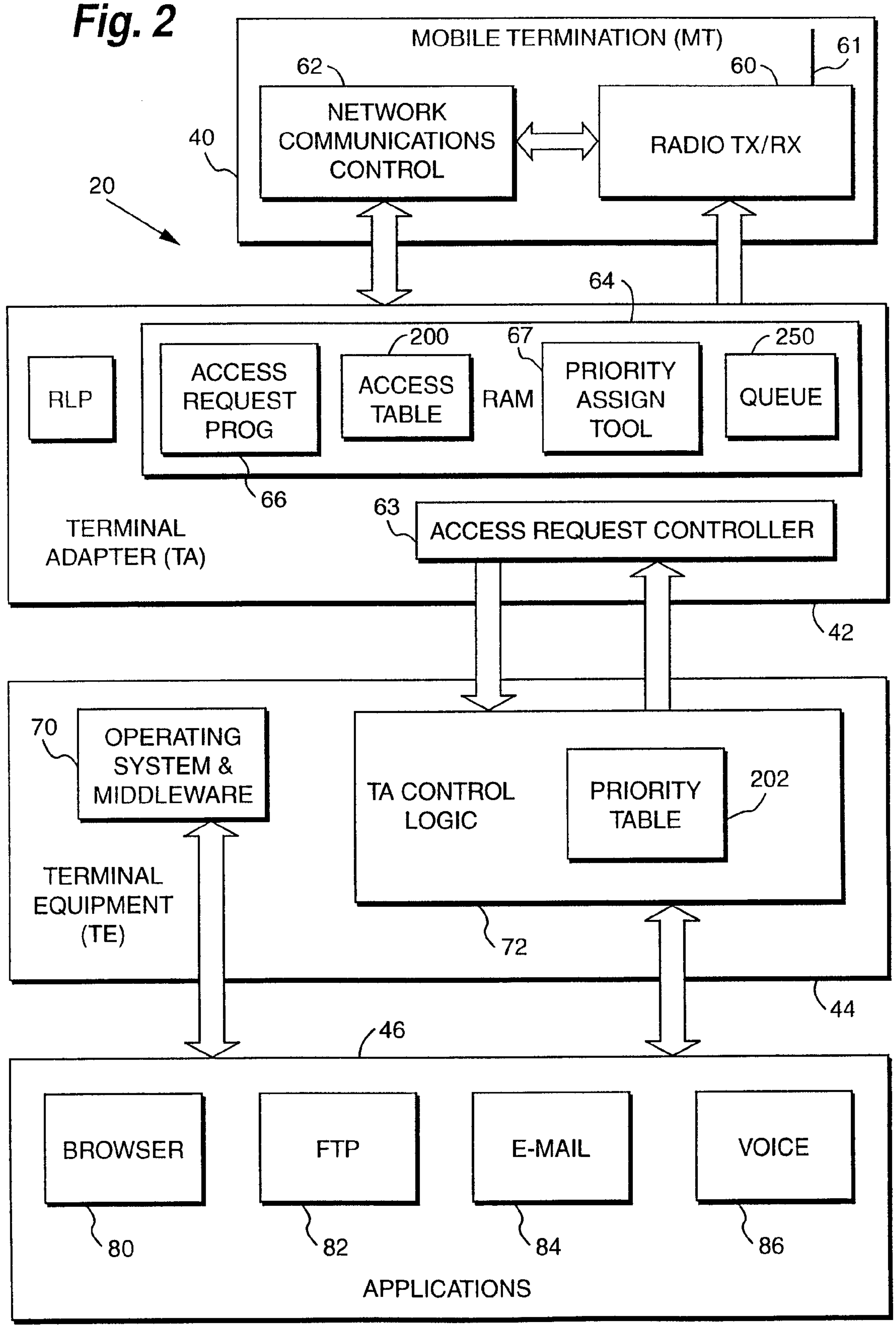
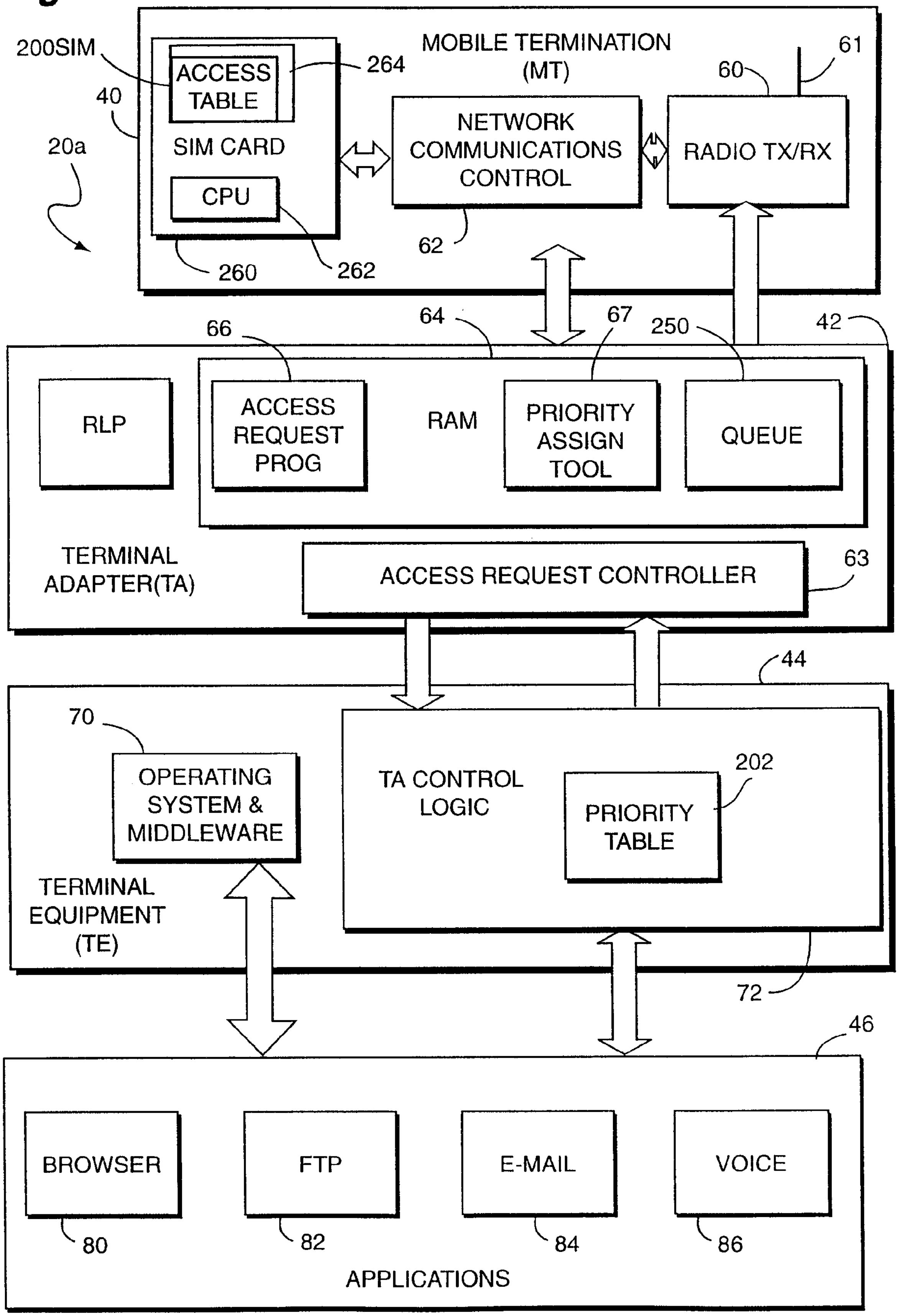

MOBILE TERMINATION (MT)
61
60
62
NETWORK COMMUNICATIONS CONTROL
RADIO TX/RX
40
20
64
200
67
250
ACCESS REQUEST PROG
ACCESS TABLE
RAM
PRIORITY ASSIGN TOOL
QUEUE
RLP
66
63
ACCESS REQUEST CONTROLLER
TERMINAL ADAPTER (TA)
42
70
OPERATING SYSTEM & MIDDLEWARE
TA CONTROL LOGIC
PRIORITY TABLE
202
TERMINAL EQUIPMENT (TE)
72
44
46
BROWSER
FTP
E-MAIL
VOICE
80
82
84
86
APPLICATIONS

Fig. 2A



200SIM
40
20a
ACCESS TABLE
264
SIM CARD
CPU
260
262
MOBILE TERMINATION (MT)
NETWORK COMMUNICATIONS CONTROL
62
RADIO TX/RX
60
61
64
66
67
250
42
RLP
ACCESS REQUEST PROG
RAM
PRIORITY ASSIGN TOOL
QUEUE
TERMINAL ADAPTER(TA)
ACCESS REQUEST CONTROLLER
63
44
70
OPERATING SYSTEM & MIDDLEWARE
TA CONTROL LOGIC
PRIORITY TABLE
202
TERMINAL EQUIPMENT (TE)
72
46
BROWSER
FTP
E-MAIL
VOICE
80
82
84
86
APPLICATIONS

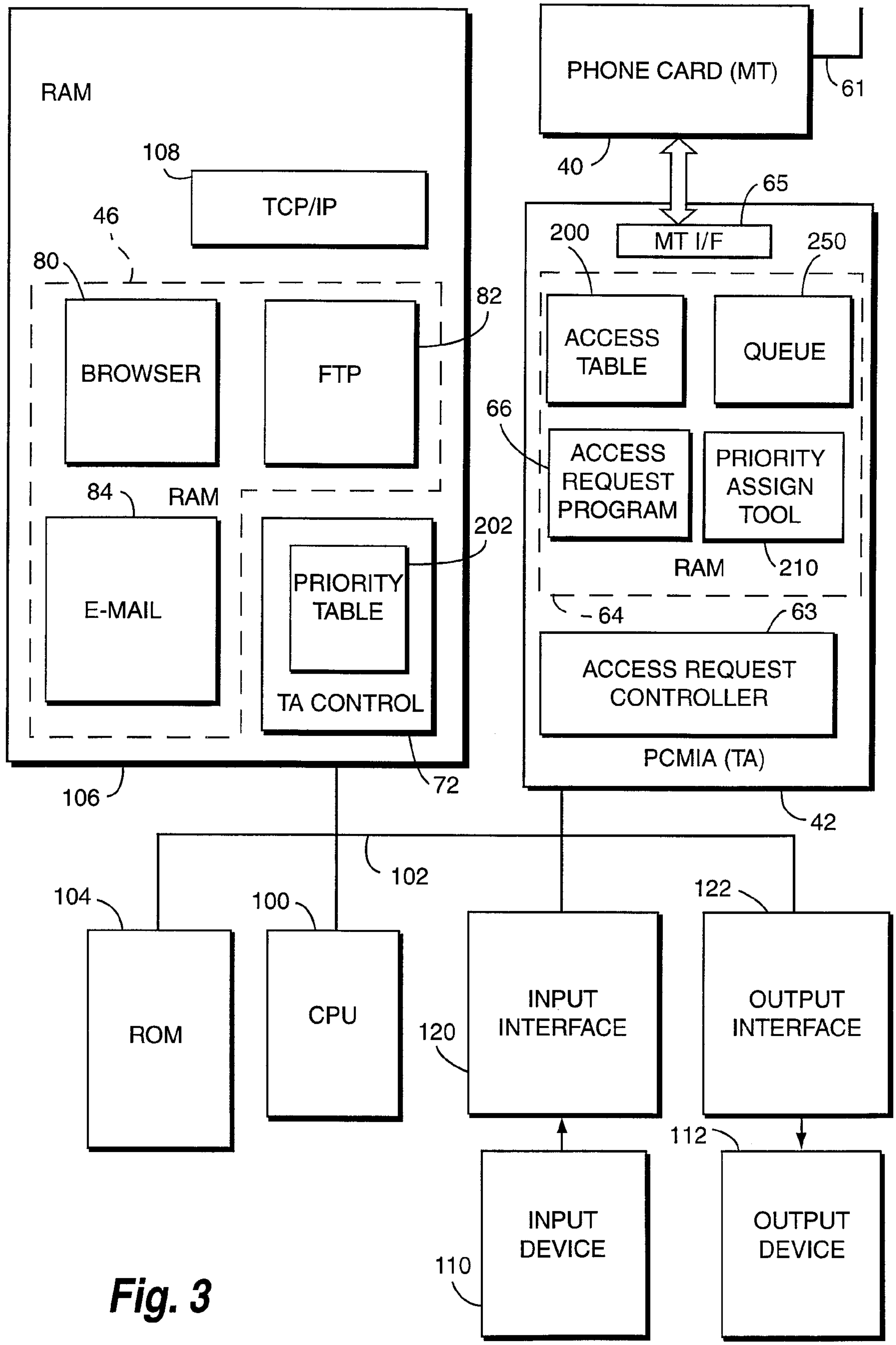
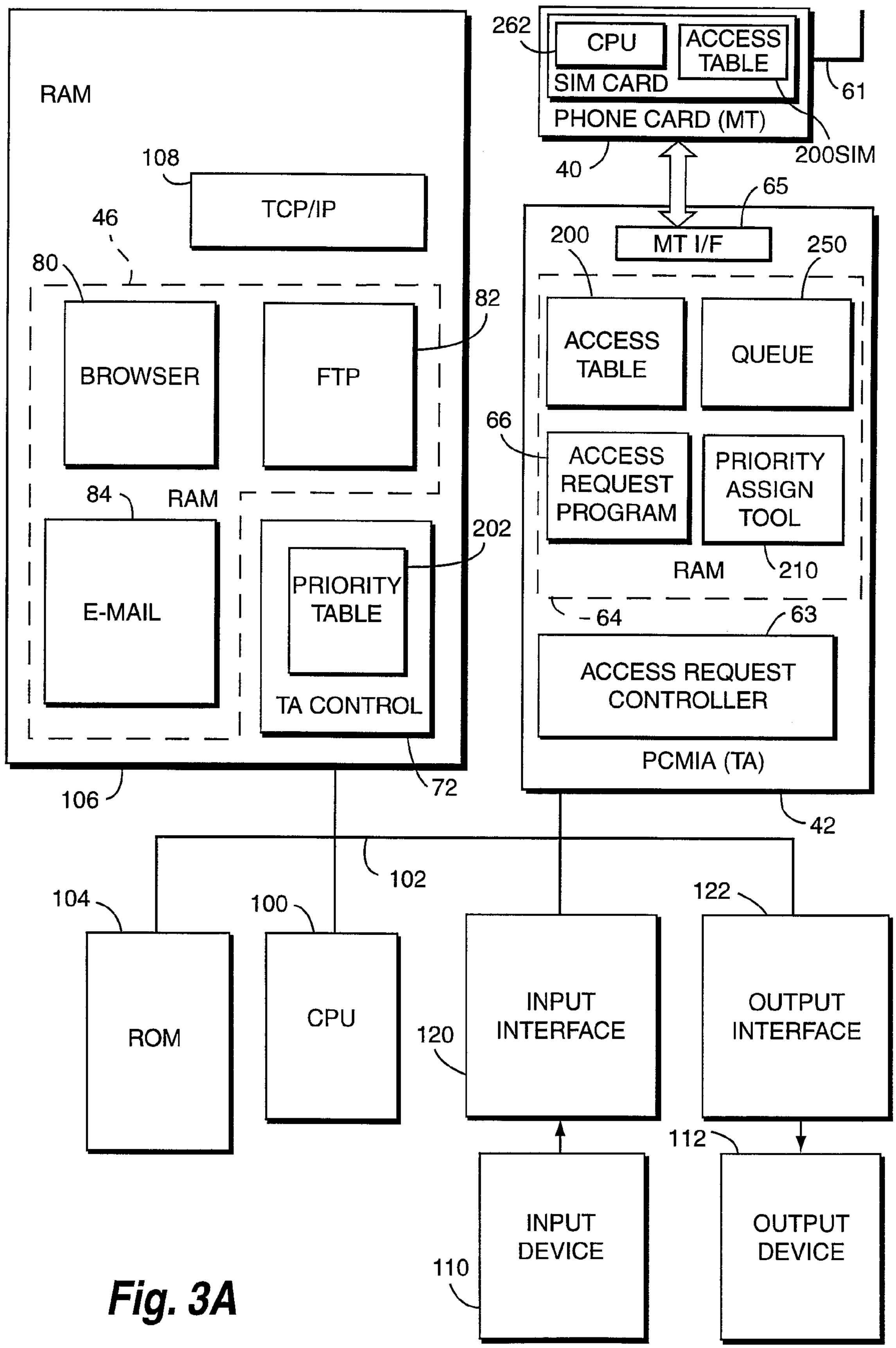

RAM
108
TCP/IP
46
80
BROWSER
FTP
82
84
RAM
E-MAIL
PRIORITY TABLE
TA CONTROL
202
106
72
PHONE CARD (MT)
61
40
65
MT I/F
200
250
ACCESS TABLE
QUEUE
66
ACCESS REQUEST PROGRAM
PRIORITY ASSIGN TOOL
RAM
210
64
63
ACCESS REQUEST CONTROLLER
PCMIA (TA)
42
102
104
100
122
ROM
CPU
120
INPUT INTERFACE
OUTPUT INTERFACE
112
INPUT DEVICE
OUTPUT DEVICE
110

Fig. 3



RAM
108
TCP/IP
46
80
BROWSER
FTP
82
84
RAM
E-MAIL
PRIORITY TABLE
202
TA CONTROL
106
72
262
CPU
ACCESS TABLE
SIM CARD
61
PHONE CARD (MT)
200SIM
40
65
MT I/F
200
250
ACCESS TABLE
QUEUE
66
ACCESS REQUEST PROGRAM
PRIORITY ASSIGN TOOL
RAM
210
64
63
ACCESS REQUEST CONTROLLER
PCMIA (TA)
42
102
104
100
122
ROM
CPU
120
INPUT INTERFACE
OUTPUT INTERFACE
112
INPUT DEVICE
OUTPUT DEVICE
110

Fig. 3A

Fig. 4

ACCESS TABLE	
ACCESS CLASSES PERMITTED BY SUBSCRIPTION AGREEMENT	ACCESS STATUS AS DETERMINED FROM NETWORK
ACCESS CLASS C0 4	PERMITTED
ACCESS CLASS C09	DENIED
ACCESS CLASS C14	DENIED

200X

Fig. 5A

8	7	6	5	4	3	2	1	
	RACH CONTROL PARAMETERS IEI							OCTET 1
MAX RETRANS		Tx-INTEGER				CELL BARR ACCESS	RE	OCTET 2
AC C15	AC C14	AC C13	AC C12	AC C11	AC C10	AC C09	AC C08	OCTET 3
AC C07	AC C06	AC C05	AC C04	AC C03	AC C02	AC C01	AC C00	OCTET 4

Fig. 6

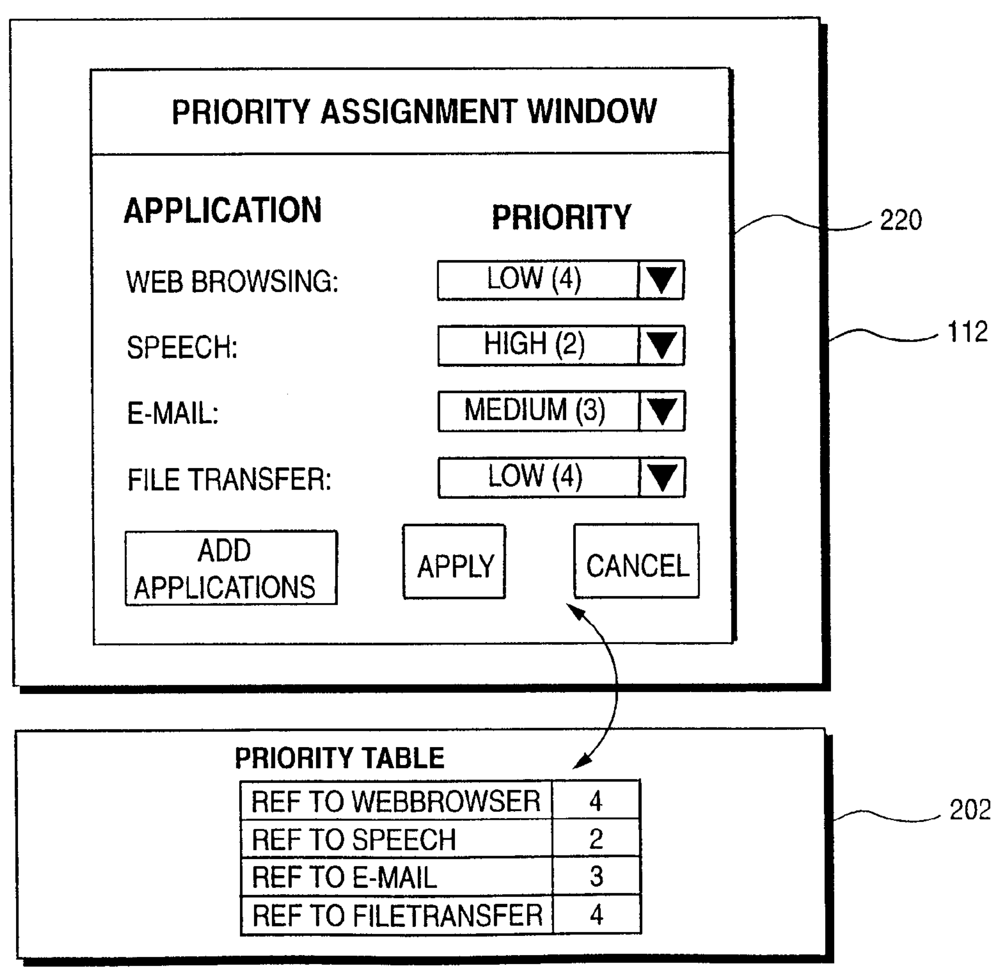


Fig. 5B

a1	a2	a3	a4	b1	b2	b3	b4	OCTET 0
c1	c2	c3	c4	d1	d2	d3	d4	OCTET 2
e1	e2	e3	e4	f1	f2	f3	f4	
g1	g2	g3	g4	h1	h2	h3	h4	
i1	i2	i3	i4	k1	k2	k3	k4	
l1	l2	l3	l4	m1	m2	m3	m4	
n1	n2	n3	n4	o1	o2	o3	o4	
p1	p2	p3	p4	q1	q2	q3	q4	
r1	r2	r3	r4	s1	s2	s3	s4	OCTET 7

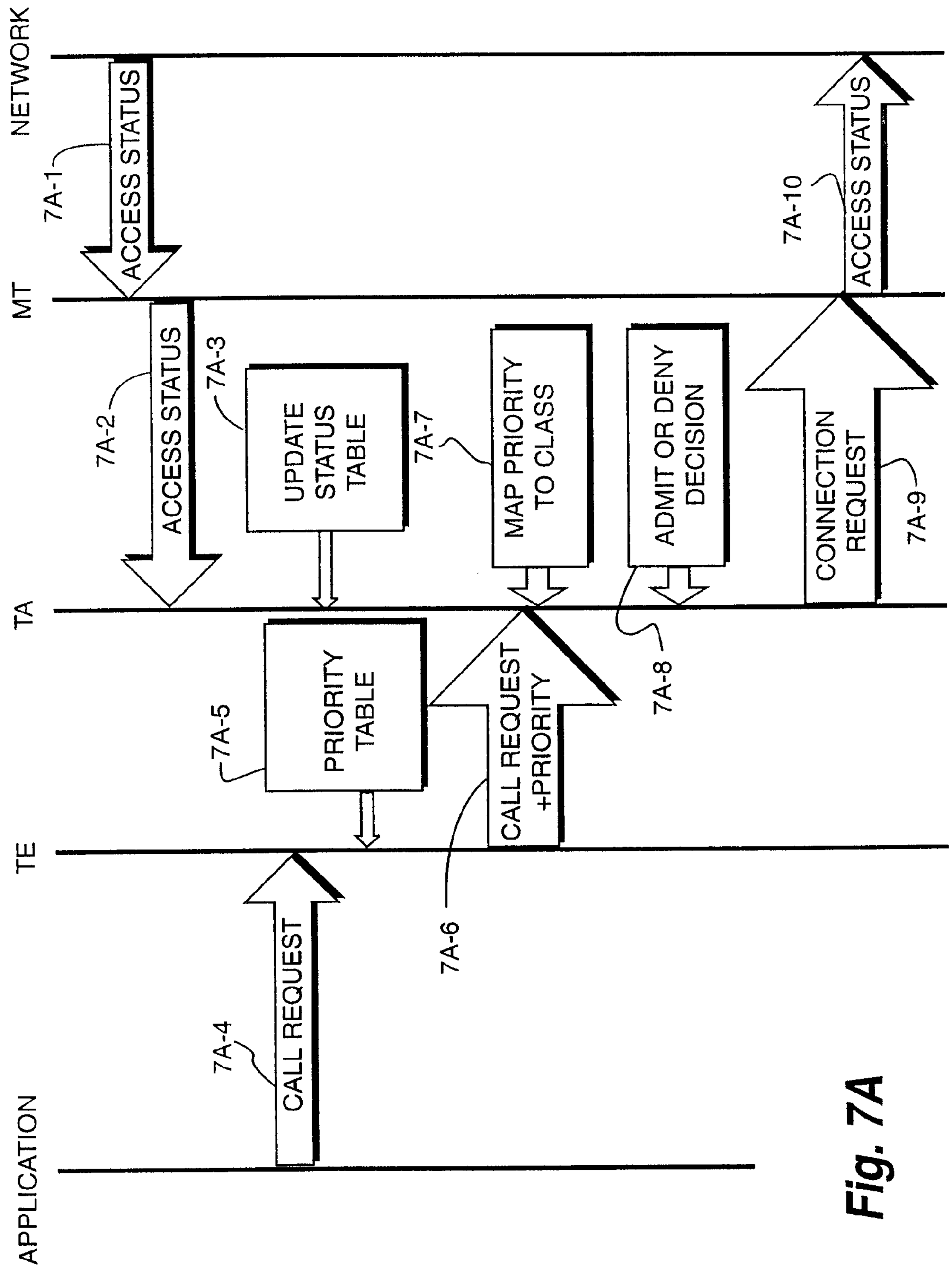

NETWORK
MT
TA
TE
APPLICATION
ACCESS STATUS
7A-1
ACCESS STATUS
7A-2
UPDATE STATUS TABLE
7A-3
CALL REQUEST
7A-4
PRIORITY TABLE
7A-5
CALL REQUEST +PRIORITY
7A-6
MAP PRIORITY TO CLASS
7A-7
ADMIT OR DENY DECISION
7A-8
CONNECTION REQUEST
7A-9
ACCESS STATUS
7A-10

Fig. 7A

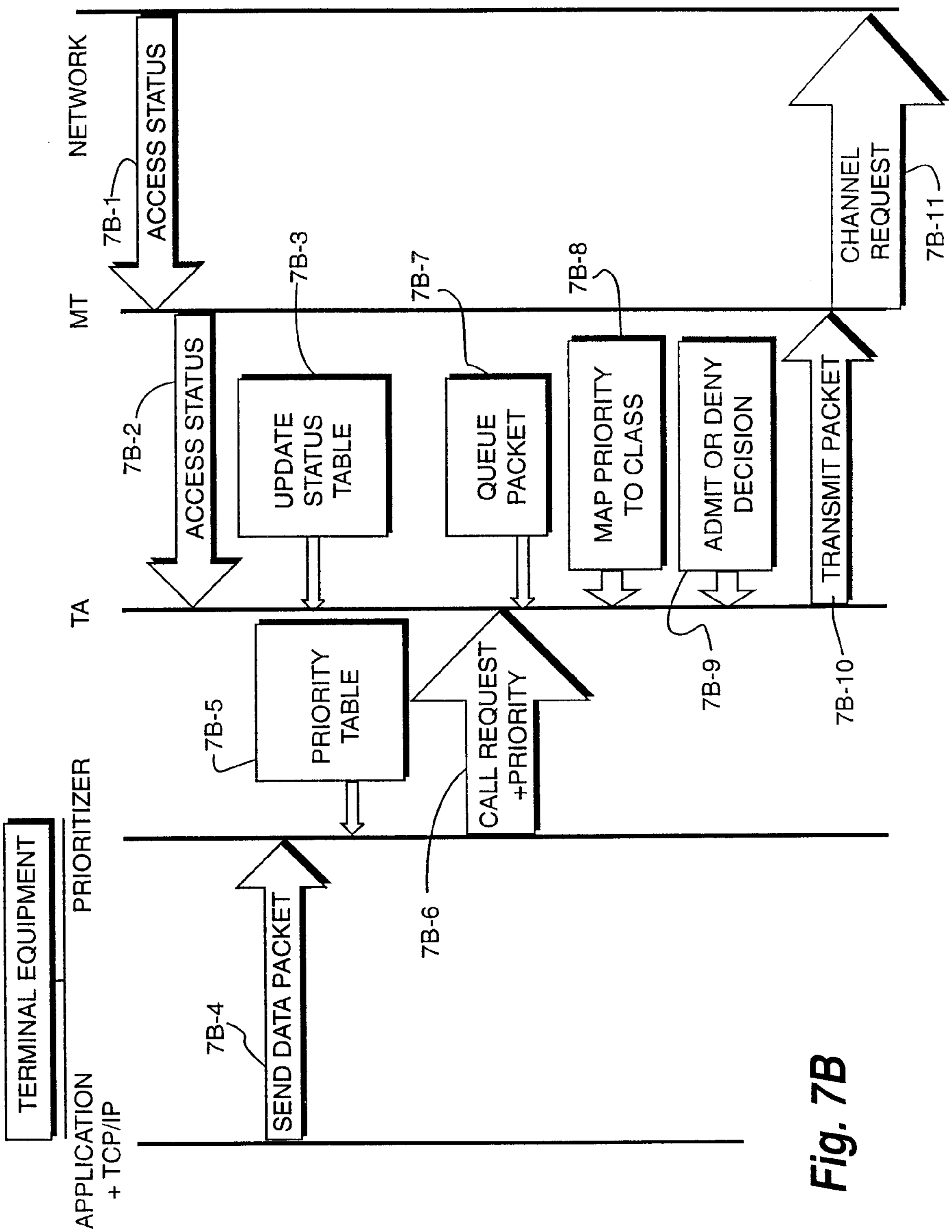
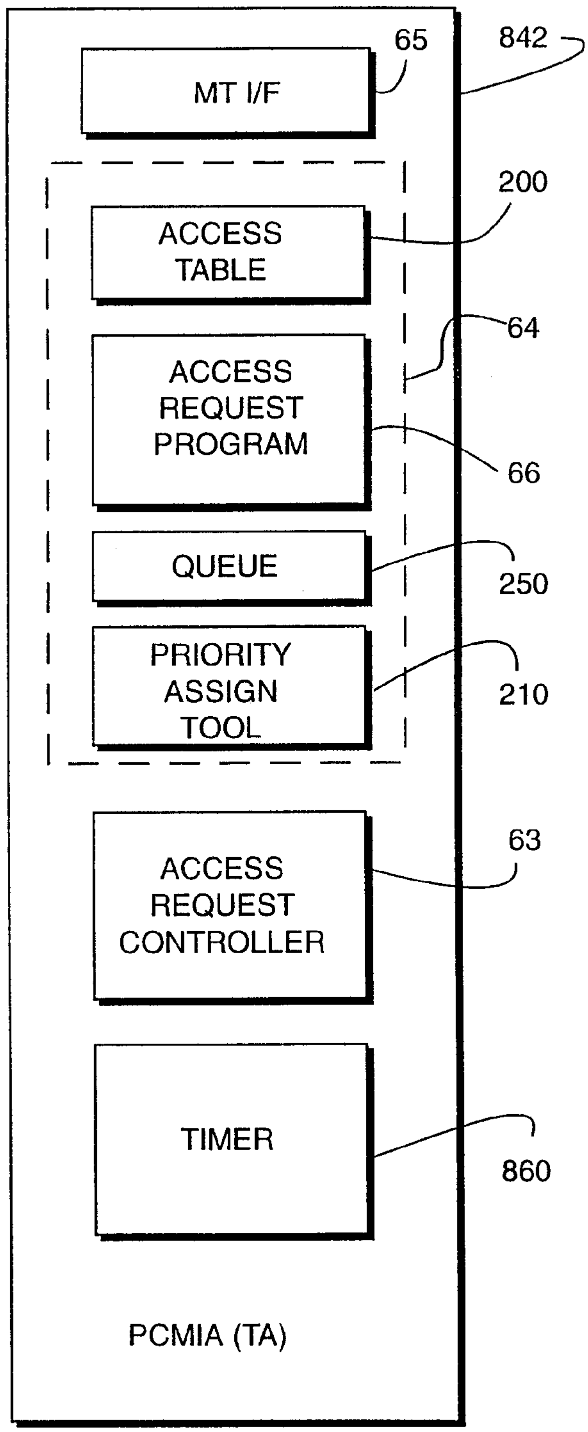
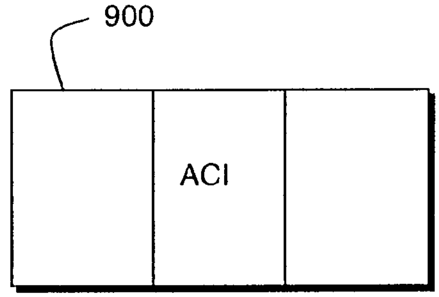

TERMINAL EQUIPMENT
APPLICATION + TCP/IP
PRIORITIZER
TA
MT
NETWORK
7B-1
ACCESS STATUS
7B-2
ACCESS STATUS
7B-3
UPDATE STATUS TABLE
7B-4
SEND DATA PACKET
7B-5
PRIORITY TABLE
7B-6
CALL REQUEST +PRIORITY
7B-7
QUEUE PACKET
7B-8
MAP PRIORITY TO CLASS
7B-9
ADMIT OR DENY DECISION
7B-10
TRANSMIT PACKET
7B-11
CHANNEL REQUEST

Fig. 7B



MT I/F
65
842
ACCESS TABLE
200
ACCESS REQUEST PROGRAM
64
66
QUEUE
250
PRIORITY ASSIGN TOOL
210
ACCESS REQUEST CONTROLLER
63
TIMER
860
PCMIA (TA)

Fig. 8



900
ACI

Fig. 10

Fig. 9

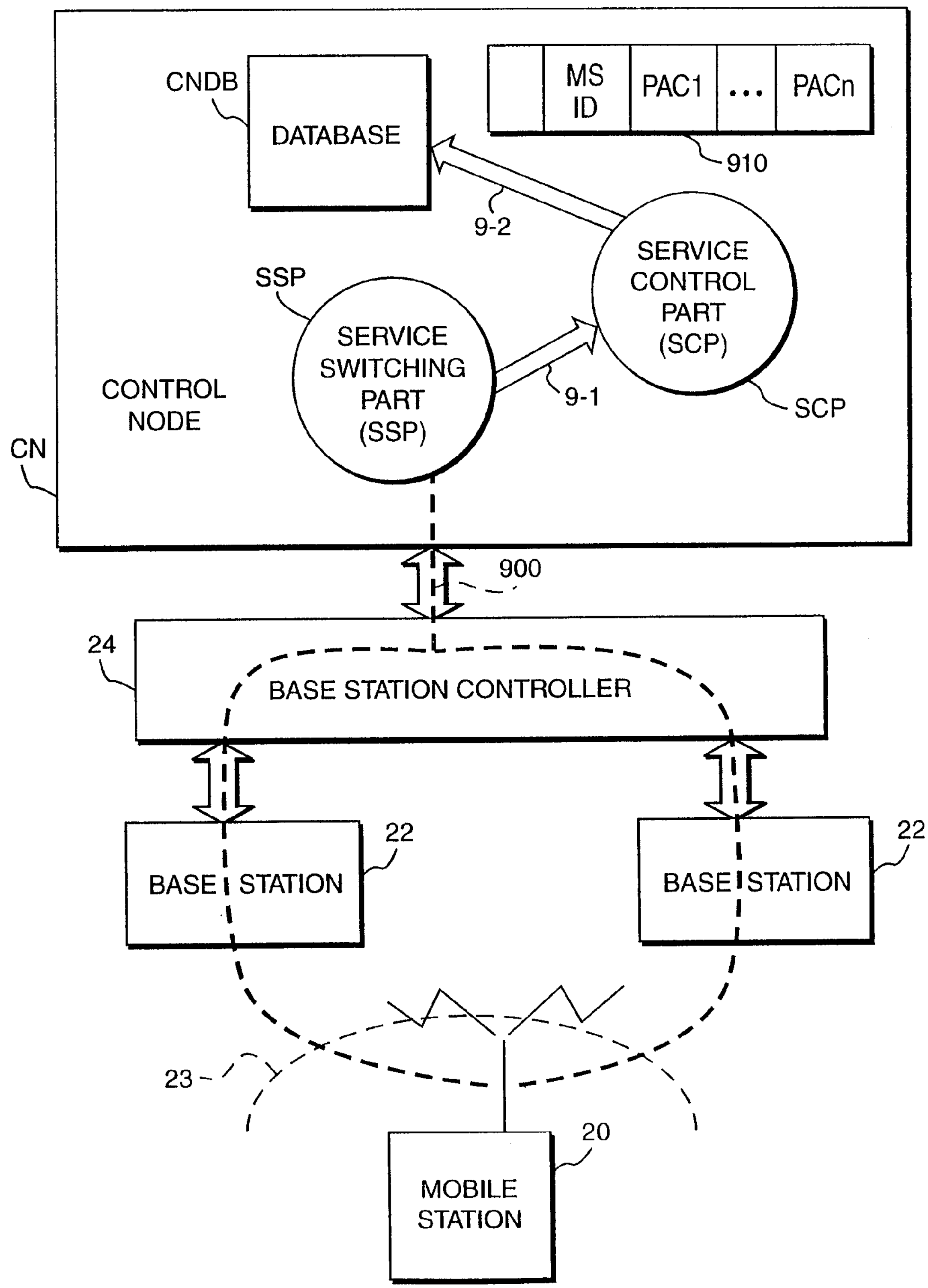
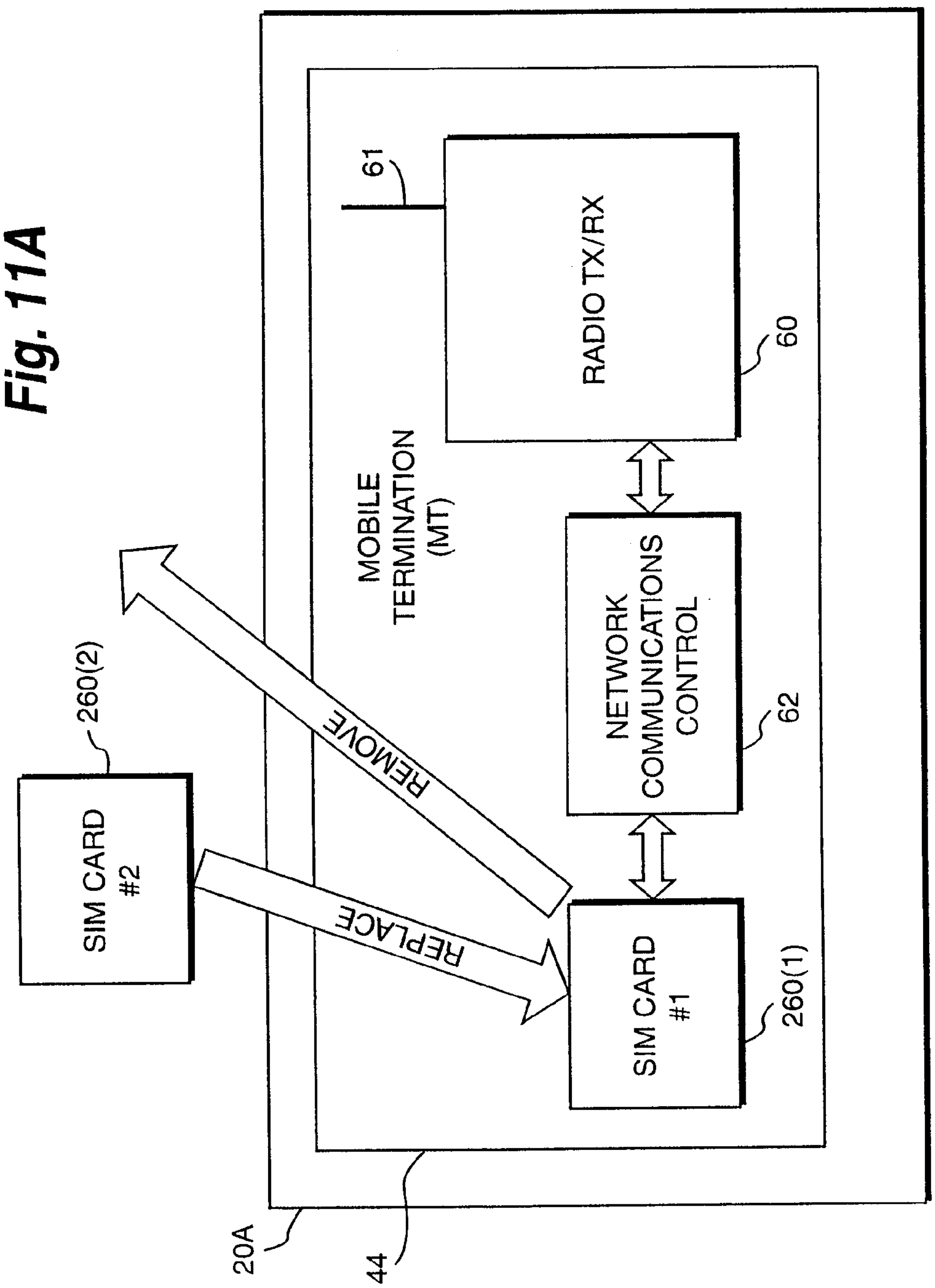

CNDB
DATABASE
MS ID
PAC1
...
PACn
910
9-2
SSP
SERVICE SWITCHING PART (SSP)
SERVICE CONTROL PART (SCP)
9-1
SCP
CONTROL NODE
CN
900
24
BASE STATION CONTROLLER
22
BASE STATION
22
BASE STATION
23
20
MOBILE STATION

Fig. 11A


SIM CARD #2
260(2)
REMOVE
REPLACE
MOBILE TERMINATION (MT)
61
RADIO TX/RX
60
NETWORK COMMUNICATIONS CONTROL
62
SIM CARD #1
260(1)
20A
44

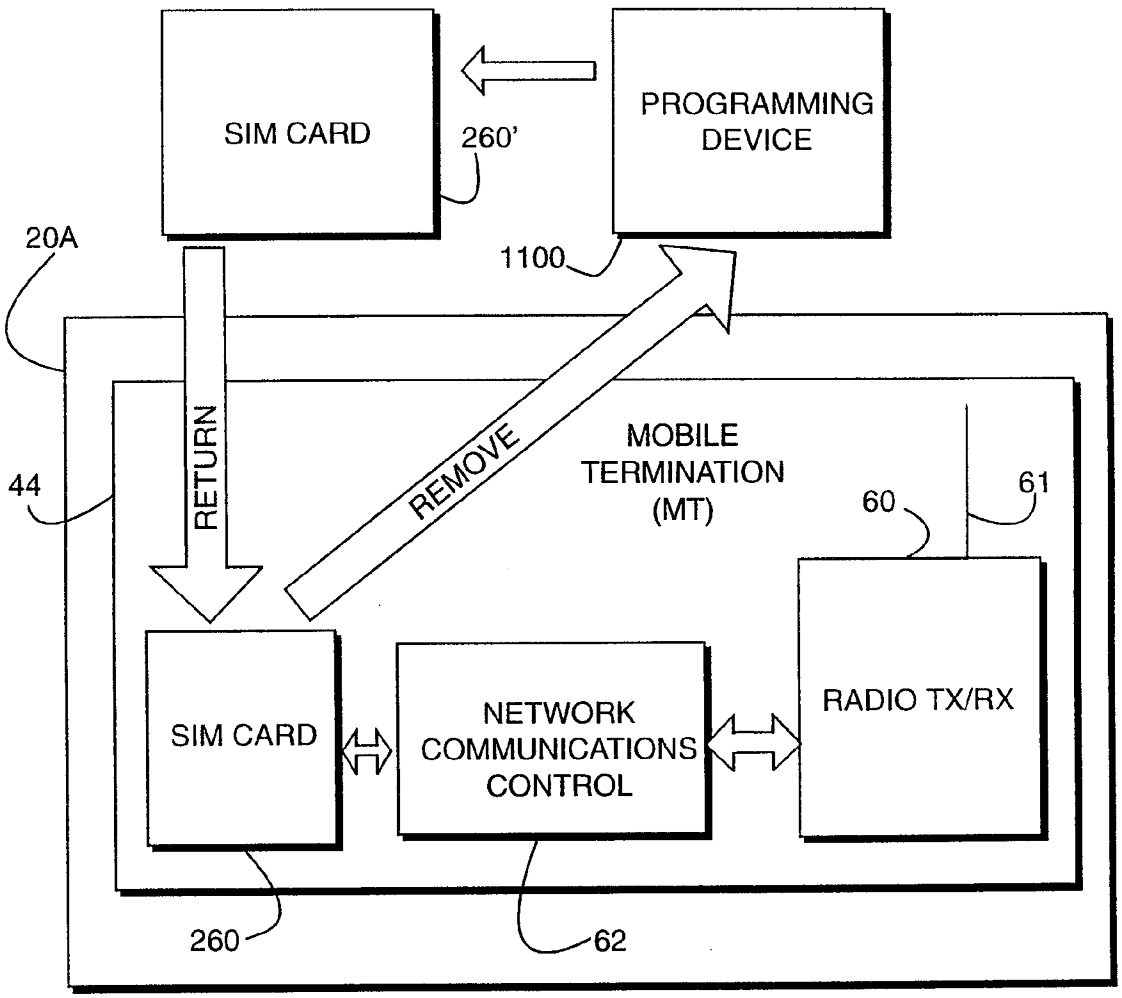

SIM CARD
260'
PROGRAMMING DEVICE
1100
20A
44
RETURN
REMOVE
MOBILE TERMINATION (MT)
60
61
SIM CARD
NETWORK COMMUNICATIONS CONTROL
RADIO TX/RX
260
62

Fig. 11B

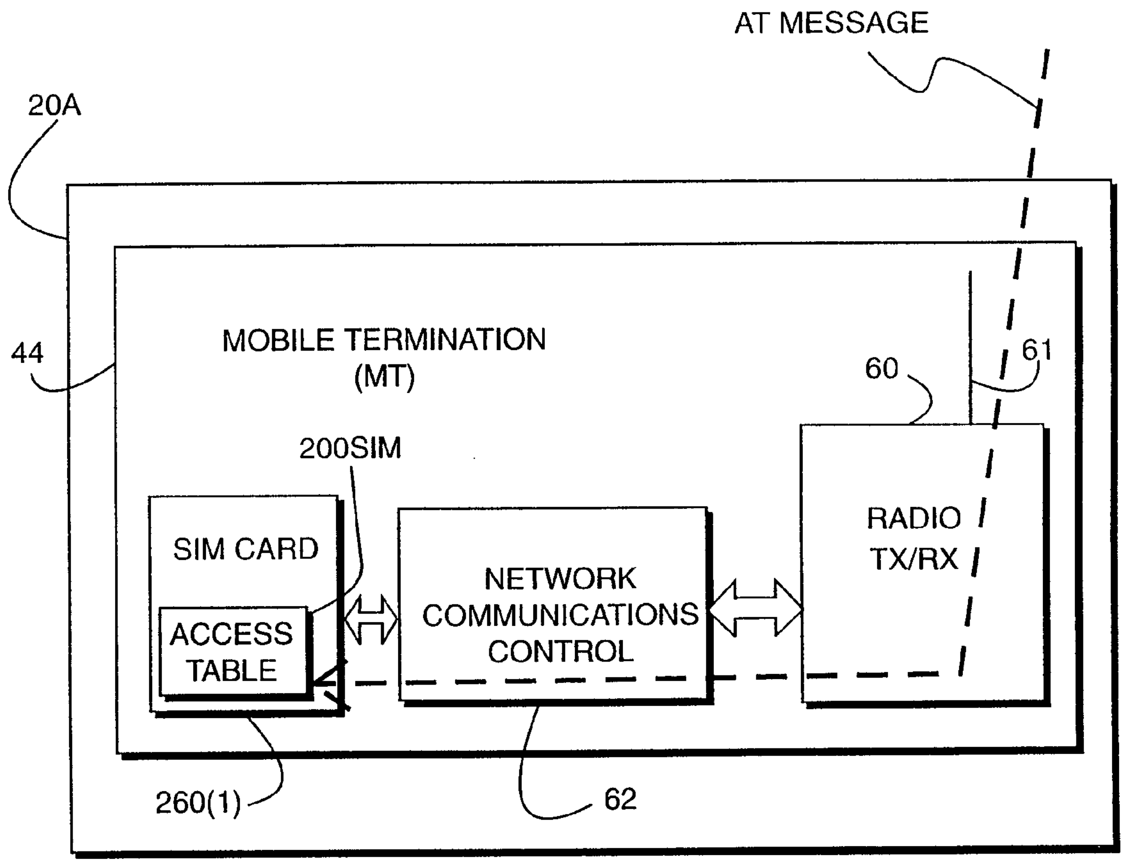

AT MESSAGE
20A
44
MOBILE TERMINATION
(MT)
60
61
200SIM
SIM CARD
ACCESS
TABLE
NETWORK
COMMUNICATIONS
CONTROL
RADIO
TX/RX
260(1)
62

Fig. 11C

INTERNATIONAL SEARCH REPORT

International Application No
PCT/SE 99/00281

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 H04Q7/32 H04L12/56 H04L29/06

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 H04Q H04L

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 95 03679 A (NOMADIC SYSTEMS INC) 2 February 1995	1,3-5, 11,12, 27,28, 30,38, 39,43
	see page 4, line 10 - line 33	
	see page 5, line 22 - page 6, line 10	
Y	see page 6, line 15 - page 7, line 6	13,40
A	see page 7, line 10 - line 24	15

X	WO 97 19525 A (MOTOROLA INC) 29 May 1997	1,3,12
	see page 4, line 1 - page 6, line 19	
	see page 10, line 13 - page 11, line 26	
A	see page 14, line 8 - line 23	15

	-/--	

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

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"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

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"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
7 June 1999	17/06/1999

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Baas, G

1

INTERNATIONAL SEARCH REPORT

International Application No
PCT/SE 99/00281

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication,where appropriate, of the relevant passages	Relevant to claim No.
X	"ETSI; Interim European Telecommunication Standard I-ETS 300022, European digital cellular telecommunication system (phase 1), Mobile radio interface layer 3 specification" GSM 04.08,May 1992, XP002088537 cited in the application see page 338 - page 340; figure 10.36; table 10.30 ---	41,42
Y	US 5 574 728 A (MAMAGHANI FARZAN ET AL) 12 November 1996 see column 1, line 11 - line 52 see column 2, line 12 - line 47 ---	13,40
A	EP 0 782 364 A (LSI LOGIC CORP) 2 July 1997 see column 3, line 6 - line 13 see column 4, line 47 - column 5, line 57 -----	1,15,27

1

INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No
PCT/SE 99/00281

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
WO 9503679 A	02-02-1995	NONE	
WO 9719525 A	29-05-1997	US 5729542 A	17-03-1998
		EP 0804834 A	05-11-1997
US 5574728 A	12-11-1996	CN 1142739 A	12-02-1997
EP 0782364 A	02-07-1997	JP 9219890 A	19-08-1997

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International Bureau

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(51) International Patent Classification 6 : H04J 11/00	A1	(11) International Publication Number: WO 98/09395 (43) International Publication Date: 5 March 1998 (05.03.98)

(21) International Application Number: PCT/US97/15384

(22) International Filing Date: 29 August 1997 (29.08.97)

(30) Priority Data:

60/025,227	29 August 1996 (29.08.96)	US
60/025,228	29 August 1996 (29.08.96)	US

(71) Applicant: THE BOARD OF TRUSTEES OF THE LELAND STANFORD JUNIOR UNIVERSITY [US/US]; Suite 350, 900 Welch Road, Palo Alto, CA 94304 (US).

(72) Inventors: RALEIGH, Gregory, G.CIOFFI, John, M.

(74) Agent: McFARLANE, Thomas, J.; 426 Lowell Avenue, Palo Alto, CA 94301 (US).

(81) Designated States: CA, JP, MX, European patent (AT, BE, CH, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE).

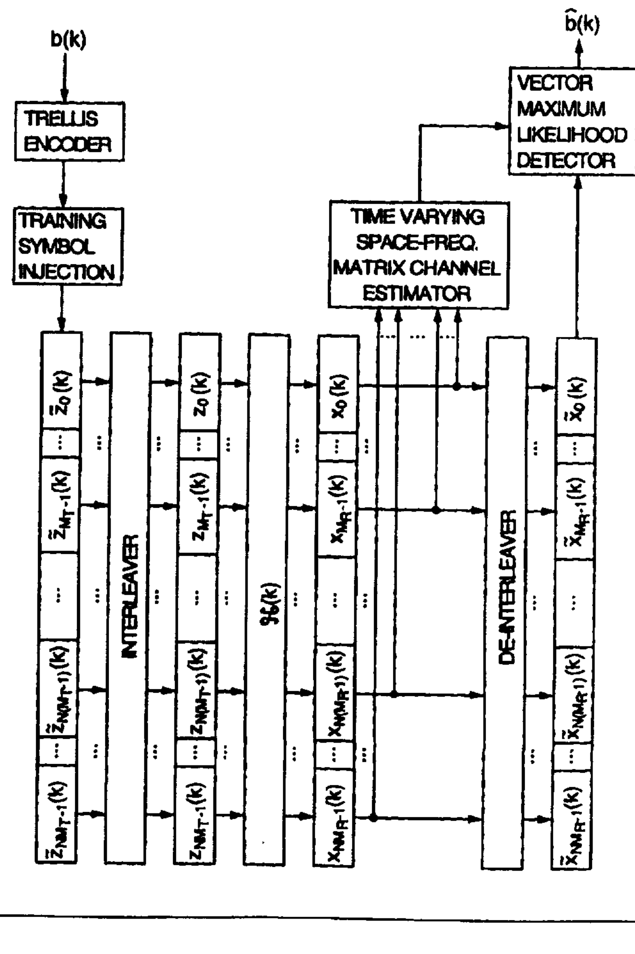
Published

With international search report.
Before the expiration of the time limit for amending the claims and to be republished in the event of the receipt of amendments.

(54) Title: HIGH CAPACITY WIRELESS COMMUNICATION USING SPATIO-TEMPORAL CODING

(57) Abstract

In a system and method of digital wireless communication between a base station (B) and a subscriber unit (S), a spatial channel characterized by a channel matrix (H) couples an adaptive array of (MT) antenna elements at the base station (B) with an adaptive array of antenna elements (MR) at the subscriber station (S). The method comprises the use of spatio-temporal coding (TRELLIS ENCODER), training symbols (TRAINING SYMBOL INJECTION), and frequency domain deinterleaving (INTERLEAVER). At the receiver, a matched de-interleaver (DE-INTERLEAVER) transforms the space-frequency sequence back into a serial signal stream. A maximum likelihood detector (VECTOR MAXIMUM LIKELIHOOD DETECTOR) generates the recovered information stream.



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DE	Germany
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EE	Estonia
ES	Spain
FI	Finland
FR	France
GA	Gabon
GB	United Kingdom
GE	Georgia
GH	Ghana
GN	Guinea
GR	Greece
HU	Hungary
IE	Ireland
IL	Israel
IS	Iceland
IT	Italy
JP	Japan
KE	Kenya
KG	Kyrgyzstan
KP	Democratic People's Republic of Korea
KR	Republic of Korea
KZ	Kazakstan
LC	Saint Lucia
LI	Liechtenstein
LK	Sri Lanka
LR	Liberia
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MG	Madagascar
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ML	Mali
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MW	Malawi
MX	Mexico
NE	Niger
NL	Netherlands
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NZ	New Zealand
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High Capacity Wireless Communication Using Spatio-Temporal Coding

RELATED APPLICATIONS

This application claims priority from U.S. provisional applications 60/025,227 and 60/025,228, both filed 08/29/96. Both applications are hereby incorporated by reference.

FIELD OF THE INVENTION

This invention relates generally to digital wireless communication systems. More particularly, it relates to using antenna arrays by both a base station and a subscriber to significantly increase the capacity of wireless communication systems.

BACKGROUND OF THE INVENTION

Due to the increasing demand for wireless communication, it has become necessary to develop techniques for more efficiently using the allocated frequency bands, i.e. increasing the capacity to communicate information within a limited available bandwidth. This increased capacity can be used to enhance system performance by increasing the number of information channels, by increasing the channel information rates and/or by increasing the channel reliability.

FIG. 1 shows a conventional low capacity wireless communication system. Information is transmitted from a base station B to subscribers $S_1, \ldots, S_9$ by broadcasting omnidirectional signals on one of several predetermined frequency channels. Similarly, the subscribers transmit information back to the base station by broadcasting similar

signals on one of the frequency channels. In this system, multiple users independently access the system through the division of the frequency band into distinct subband frequency channels. This technique is known as frequency division multiple access (FDMA).

A standard technique used by commercial wireless phone systems to increasing capacity is to divide the service region into spatial cells, as shown in FIG. 2. Instead of using just one base station to serve all users in the region, a collection of base stations $B_1, \ldots, B_7$ are used to independently service separate spatial cells. In such a cellular system, multiple users can reuse the same frequency channel without interfering with each other, provided they access the system from different spatial cells. The cellular concept, therefore, is a simple type of spatial division multiple access (SDMA).

In the case of digital communication, additional techniques can be used to increase capacity. A few well known examples are time division multiple access (TDMA) and code division multiple access (CDMA). TDMA allows several users to share a single frequency channel by assigning their data to distinct time slots. CDMA is normally a spread-spectrum technique that does not limit individual signals to narrow frequency channels but spreads them throughout the frequency spectrum of the entire band. Signals sharing the band are distinguished by assigning them different orthogonal digital code sequences. These techniques use digital coding to make more efficient use of the available spectrum.

Wireless systems may also use combinations of the above techniques to increase capacity, e.g. FDMA/CDMA and TDMA/CDMA. Although these and other known techniques increase the capacity of wireless communication systems, there is still a need to further increase system performance. Recently, considerable attention has focused on ways to increasing capacity by further exploiting the spatial domain.

One well-known SDMA technique is to provide the base station with a set of independently controlled directional antennas, thereby dividing the cell into separate sectors, each controlled by a separate antenna. As a result, the frequency reuse in the system can be increased and/or cochannel interference can be reduced. Instead of independently controlled directional antennas, this technique can also be implemented with a coherently controlled antenna array, as shown in FIG. 3. Using a signal processor to control the relative phases of the signals applied to the antenna elements, predetermined beams can be formed in the directions of the separate sectors. Similar signal processing can be used to selectively receive signals only from within the distinct sectors.

In an environment containing a significant number of reflectors (such as buildings), a signal will often follow multiple paths. Because multipath reflections alter the signal directions, the cell space experiences angular mixing and can not be sharply divided into distinct sectors. Multipath can therefore cause cochannel interference between sectors, reducing the benefit of sectoring the cell. In addition, because the separate parts of such a multipath signal can arrive with different phases that destructively interfere, multipath can result in unpredictable signal fading.

In order to avoid the above problems with multipath, more sophisticated SDMA techniques have been proposed. For example, U.S. Pat. No. 5,471,647 and U.S. Pat. No. 5,634,199, both to Gerlach et al., and U.S. Pat. No. 5,592,490 to Barratt et al. disclose wireless communication systems that increase performance by exploiting the spatial domain. In the downlink, the base station determines the spatial channel of each subscriber and uses this channel information to adaptively control its antenna array to form customized beams,

as shown in FIG. 4A. These beams transmit an information signal x over multiple paths so that the signal x arrives to the subscriber with maximum strength. The beams can also be selected to direct nulls to other subscribers so that cochannel interference is reduced. In the uplink, as shown in FIG. 4B, the base station uses the channel information to spatially filter the received signals so that the transmitted signal x' is received with maximum sensitivity and distinguished from the signals transmitted by other subscribers. In this approach the same information signal follows several paths, providing increased spatial redundancy.

In the uplink, there are well known signal processing techniques for estimating the spatial channel from the signals received at the base station antenna array, e.g. by using *a priori* spatial or temporal structures present in the signal, or by blind adaptive estimation. If the uplink and downlink frequencies are the same, then the spatial channel for the downlink is directly related to the spatial channel for the uplink, and the base can use the known uplink channel information to perform transmit beamforming in the downlink. Because the spatial channel is frequency dependent and the uplink and downlink frequencies are often different, the base does not always have sufficient information to derive the downlink spatial channel information. One technique for obtaining downlink channel information is for the subscriber to periodically transmit test signals to the base on the downlink frequency rather than the uplink frequency. Another technique is for the base to transmit test signals and for the subscriber to feedback channel information to the base. If the spatial channel is quickly changing due to the relative movement of the base, the subscriber and/or reflectors in the environment, then the spatial channel must be updated frequently, placing a heavy demand on the system. One method to reduce the required feedback rates is to track only the subspace spanned by the time-averaged channel vector, rather than the instantaneous channel vector. Even with this

reduction, however, the required feedback rates are still a large fraction of the signal information rate.

Although these adaptive beamforming techniques require substantial signal processing and/or large feedback rates to determine the spatial channel in real time, these techniques have the advantage that they can navigate the complex spatial environment and avoid, to some extent, the problems introduced by multipath reflections. As a result, an increase in performance is enjoyed by adaptive antenna array systems, due to their use of the spatial dimension. Note, however, that while the base station antenna array can make efficient use of the spatial dimension by selectively directing the downlink signal to the subscriber S, the uplink signal in these systems is spatially inefficient. Typically, the subscriber is equipped with only a single antenna that radiates signal energy in all directions, potentially causing cochannel interference. These communication systems, therefore, do not make optimal use of the spatial dimension to increase capacity.

OBJECTS AND ADVANTAGES OF THE INVENTION

Accordingly, it is a primary object of the present invention to provide a communication system that significantly increases the capacity and performance of wireless communication systems by taking maximum advantage of the spatial domain. Another object of the invention is to provide computationally efficient coding techniques that make optimal use of the spatial dimensions of the channel. In particular, it is an object of the present invention to provide coding techniques specially adapted for the case of rapidly fading channels where channel state information (CSI) at the transmitter is unknown. These and other objects and advantages will become apparent from the following description and associated drawings.

SUMMARY OF THE INVENTION

These objects and advantages are attained by a method of digital wireless communication that takes maximal advantage of spatial channel dimensions between a base station and a subscriber unit to increase system capacity and performance. Surprisingly, the techniques of the present invention provide an increased information capacity in multipath environments. In contrast, known techniques suffer in the presence of multipath and do not exploit multipath to directly increase system capacity. In brief, the present invention teaches a method of wireless communication using antenna arrays at both the base and subscriber units to transmit distinct information signals over different spatial channels in parallel, thereby multiplying the capacity between the base and the subscriber. In particular, the present invention teaches specific spatio-temporal coding techniques that make optimal use of these additional spatial subchannels in the case of unknown transmitter channel state information.

Generally, the present invention provides a method of digital wireless communication between a base station and a subscriber unit in the case where channel state information is not known by the transmitter. For this purpose a spatio-temporal coding structure that exploits the spatial subchannel capacity is used. In particular, a matrix orthogonal frequency division multiplexing (MOFDM) scheme and a space-frequency trellis coding system is used at the transmitter, and a space-frequency maximum likelihood detector with a channel estimator are used at the receiver. With this relatively simple structure, a MIMO system according to the present invention is able to provide a channel capacity several times greater than can be achieved in a conventional wireless system using OFDM. The inventors also propose an efficient channel estimation algorithm for the time varying MIMO channel.

DESCRIPTION OF THE FIGURES

FIG. 1 shows a low capacity wireless communication system well known in the prior art.

FIG. 2 illustrates a known technique of spatially dividing a service region into cells in order to increase system capacity.

FIG. 3 illustrates the use of beamforming with an antenna array to divide a cell into angular sectors, as is known in the art.

FIGS. 4A and 4B illustrate state-of-the-art techniques using adaptive antenna arrays for downlink and uplink beamforming, respectively.

FIGS. 5A and 5B show the parallel transmission of distinct information signals using spatial subchannels in downlink and uplink, respectively, as taught by the present invention.

FIGS. 6A and 6B are physical and schematic representations, respectively, of a communication channel for a system with multiple transmitting antennas and multiple receiving antennas, according to the present invention.

FIGS. 7A and 7B are block diagrams of the system architecture for communicating information over a multiple-input-multiple-output spatial channel according to the present invention.

DETAILED DESCRIPTION

Although the following detailed description contains many specifics for the purposes of illustration, anyone of ordinary skill in the art will appreciate that many variations and alterations to the following details are within the scope of the invention. Accordingly, the following preferred embodiment of the invention is set forth without any loss of generality to, and without imposing limitations upon, the claimed invention.

As discussed above in relation to FIGS. 4A and 4B, prior art wireless systems employing an adaptive antenna array at the

base station are multiple-input-single-output (MISO) systems, i.e. the channel from the base to the subscriber is characterized by multiple inputs at the transmitting antenna array and a single output at the receiving subscriber antenna. Because these MISO systems can exploit some of the spatial channel, they have an increased capacity as compared to single-input-single-output (SISO) systems that are discussed above in relation to FIGS. 1 and 2. It should be noted that although the MISO systems disclosed in the prior art provide an increase in overall system capacity by spatially isolating separate subscribers from each other, these systems do not provide an increase in the capacity of information transmitted from the base to a single subscriber, or vice versa. As shown in FIGS. 4A and 4B, only one information signal is transmitted between the base and subscriber in both downlink and uplink of a MISO system. Even in the case where the subscriber is provided with an antenna array, the prior art suggests only that this capability would further reduce cochannel interference. Although the overall system capacity could be increased, this would not increase the capacity between the base and a single subscriber.

The present invention, in contrast, is a multiple-input-multiple-output (MIMO) wireless communication system that is distinguished by the fact that it increases the capacity of both uplink and downlink transmissions between a base and a subscriber through a novel use of additional spatial channel dimensions. The present inventors have recognized the possibility of exploiting multiple parallel spatial subchannels between a base station and a subscriber, thereby making use of additional spatial dimensions to increase the capacity of wireless communication. Surprisingly, this technique provides an increased information capacity and performance in multipath environments, a result that is in striking contrast with conventional wisdom.

FIGS. 5A and 5B illustrate a MIMO wireless communication system according to the present invention. As shown in FIG. 5A, a base station B uses adaptive antenna arrays and spatial processing to transmit distinct downlink signals x_1, x_2, x_3 through separate spatial subchannels to a subscriber unit S which uses an adaptive array and spatial processing to receive the separate signals. In a similar manner, the subscriber S uses an adaptive array to transmit distinct uplink signals x'_1, x'_2, x'_3 to the base B over the same spatial subchannels. As the multipath in the environment increases, the channel acquires a richer spatial structure that allows more subchannels to be used for increased capacity.

It is important to note that the simple assignment of the distinct signals to the distinct spatial paths in a one-to-one correspondence, as illustrated above, is only one possible way to exploit the additional capacity provided by the spatial subchannel structure. For example, coding techniques can be used to mix the signal information among the various paths. In addition, the present inventors have developed techniques for coupling these additional spatial dimensions to available temporal and/or frequency dimensions prior to transmission. Although such coupled spatio-temporal coding techniques are more subtle than direct spatial coding alone, they provide better system performance, as will be described in detail below.

It is also important to note that the transmit beamforming at the base requires knowledge of the downlink channel state information. (Similarly, the transmit beamforming at the subscriber requires knowledge of the uplink channel state information. Because the system is symmetric with respect to the base and subscriber, it suffices to discuss one case.) Although downlink channel state information can be fed back to the base from the subscriber, if the channel is rapidly changing, then the demand on the channel capacity to provide real time channel information and the demand on the signal

processing may make it impractical to implement the system under the assumption that transmit channel state information is available. Accordingly, the inventors have developed an MOFDM coding technique to take advantage of the added spatial subchannels even in the case of unknown transmitter channel state information.

In order to facilitate an understanding of the present invention and enable those skilled in the art to practice it, the following description includes a teaching of the general principles of the invention, as well as implementation details. First we develop a compact model for understanding frequency dispersive, spatially selective wireless MIMO channels in the case where the channels are time invariant, and then generalize to the case where the channels vary with time. We then discuss the theoretical information capacity limits of these channels, and propose spatio-temporal coding structures that exploit the spatial subchannel capacity in the case of unknown channel state information. In particular, a matrix orthogonal frequency division multiplexing (MOFDM) scheme is described. In a preferred embodiment a space-frequency trellis coding system is located at the transmitter, and a space-frequency maximum likelihood detector with a channel estimator are located at the receiver. With this relatively simple structure, a MIMO system according to the present invention is able to provide a channel capacity several times greater than can be achieved in a conventional wireless system using OFDM. The inventors also propose an efficient channel estimation algorithm for the time varying MIMO channel.

In its preferred implementations, the present invention makes use of many techniques and devices well known in the art of adaptive antenna arrays systems and associated digital beamforming signal processing. These techniques and devices are described in detail in U.S. Pat. No. 5,471,647 and U.S. Pat. No. 5,634,199, both to Gerlach et al., and U.S. Pat. No.

5,592,490 to Barratt et al., which are all incorporated herein by reference. In addition, a comprehensive treatment of the present state of the art is given by John Livita and Titus Kwok-Yeung Lo in *Digital Beamforming in Wireless Communications* (Artech House Publishers, 1996). Accordingly, the following detailed description focuses upon the specific signal processing techniques which are required to enable those skilled in the art to practice the present invention.

Consider first a time-invariant communication channel for a system with M_T transmitting antennas at a base B and M_R receiving antennas at a subscriber S, as illustrated in FIGS. 6A and 6B. The channel input at a sample time k can be represented by an M_T dimensional column vector

$$\mathbf{z}(k) = [z_1(k), \ldots, z_{M_T}(k)]^T,$$

and the channel output and noise for sample k can be represented, respectively, by M_R dimensional column vectors

$$\mathbf{x}(k) = [x_1(k), \ldots, x_{M_R}(k)]^T,$$

and

$$\mathbf{n}(k) = [n_1(k), \ldots, n_{M_R}(k)]^T.$$

The communication over the channel $\mathbf{H}$ may then be expressed as a vector equation

$$\mathbf{x}(k) = \mathbf{Hz}(k) + \mathbf{n}(k),$$

where the MIMO channel matrix is

$$\mathbf{H} = \begin{pmatrix} h_{1,1} & \ldots & h_{1,M_T} \\ \vdots & & \vdots \\ h_{M_R,1} & \ldots & h_{M_R,M_T} \end{pmatrix}.$$

Each matrix element h_{ij} represents the SISO channel between the i^{th} receiver antenna and the j^{th} transmitter antenna. Due to the multipath structure of the spatial channel, orthogonal

spatial subchannels can be determined by calculating the independent modes (e.g. eigenvectors) of the channel matrix **H**. These spatial subchannels can then be used to transmit independent signals and increase the capacity of the communication link between the base B and the subscriber S.

In the case where the channel matrix **H** is not fixed in time, but changes, it should be represented as a time-dependent matrix, **H**(k). Moreover, because the multipath introduces time delays into the various propagation paths, a spatial decomposition of **H** independent of time will result in temporal mixing of the signals. It is more appropriate, therefore, to perform a more general spatio-temporal analysis of the channel.

Let $\{z_j(n)\}$ be a digital symbol sequence to be transmitted from the j^{th} antenna element, g(t) a pulse shaping function impulse response, and T the symbol period. Then the signal applied to the j^{th} antenna element at time t is given by

$$s_j(t) = \sum_n z_j(n) g(t-nT)$$

The pulse shaping function is typically the convolution of two separate filters, one at the transmitter and one at the receiver. The optimum receiver filter is a matched filter. In practice, the pulse shape is windowed resulting in a finite duration impulse response. We assume synchronous complex baseband sampling with symbol period T. We define n_0 and $(\nu+1)$ to be the maximum lag and length over all paths l for the windowed pulse function sequences $\{g(nT - \tau_l)\}$. To simplify notation, it is assumed that $n_0 = 0$, and the discrete-time notation $g(nT - \tau_l) = g_l(n)$ is adopted.

When a block of N data symbols are transmitted, $N+\nu$ non-zero output samples result. Denoting k as the block index for the k^{th} channel usage, $k(N+\nu)$ is the discrete time index for the

first received sample, and $(k+1)(N+\nu)-1$ is the time index for the last received sample. The composite channel output can now be written as an $M_R\cdot(N+\nu)$ dimensional column vector with all time samples for a given receive antenna appearing in order so that

$$\mathbf{x}(k) = [x_1(k(N+\nu)),\ldots,x_1((k+1)(N+\nu)-1),\ldots,\\ x_{M_R}(k(N+\nu)),\ldots,x_{M_R}((k+1)(N+\nu)-1)]^T,$$

with an identical stacking for the output noise samples $\mathbf{n}(k)$. Similarly, the channel input is an $M_T\cdot N$ dimensional column vector written as

$$\mathbf{z}(k) = [z_1(k(N+\nu)),\ldots,z_1(k(N+\nu)+N-1),\ldots,\\ z_{M_T}(k(N+\nu)),\ldots,z_{M_T}(k(N+\nu)+N-1)]^T,$$

The spatio-temporal communication over the channel $\mathbf{H}(k)$ may then be expressed as a vector equation

$$\mathbf{x}(k) = \mathbf{H}(k)\mathbf{z}(k) + \mathbf{n}(k),$$

where the MIMO time-dependent channel matrix

$$\mathbf{H}(k) = \begin{pmatrix} \mathbf{H}_{1,1}(k) & \ldots & \mathbf{H}_{1,M_T}(k) \\ \vdots & & \vdots \\ \mathbf{H}_{M_R,1}(k) & \ldots & \mathbf{H}_{M_R,M_T}(k) \end{pmatrix}$$

is composed of SISO sub-blocks $\mathbf{H}_{ij}(k)$.

To clearly illustrate the effect of multipath, the channel can be written as the sum over multipath components

$$H(k) = \sum_{l=1}^{L} \begin{bmatrix} a_{R,1}(\theta_{R,l})\mathbf{I} \\ \vdots \\ a_{R,M_R}(\theta_{R,l})\mathbf{I} \end{bmatrix} \beta_l(k)\mathbf{G}_l \left[a_{T,1}(\theta_{T,l})\mathbf{I} \ \ldots \ a_{T,M_T}(\theta_{T,l})\mathbf{I} \right].$$

In this equation, $a_{R,j}(\theta_{R,l})$ is the gain response of the j^{th} receiver array element due to angle of arrival $\theta_{R,l}$ of the l^{th} multipath signal, $a_{T,i}(\theta_{T,l})$ is the gain response of the i^{th} transmitter array element due to angle of departure $\theta_{T,l}$ of the l^{th} multipath signal. $\mathfrak{B}_l(k)$ is the diagonal time varying channel fading parameter matrix given by

$$\mathfrak{B}_l(k) = \mathrm{diag}\,[\ \beta_l(k(N+\nu)), \ldots, \beta_l((k+1)(N+\nu)-1)\ ],$$

and the Toeplitz pulse shaping matrix $\mathbf{G}_l$ is given by

$$\mathbf{G}_l = \begin{bmatrix} g_l(0) & 0 & 0 & 0 & \ldots & 0 \\ \vdots & \ddots & & \vdots & & \vdots \\ g_l(\nu) & \ldots & g_l(0) & 0 & & 0 \\ 0 & g_l(\nu) & \ldots & g_l(0) & 0 & 0 \\ \vdots & & \ddots & & \ddots & \\ 0 & & 0 & g_l(\nu) & \ldots & g_l(0) \\ \vdots & & \vdots & & \ddots & \vdots \\ 0 & \ldots & 0 & 0 & 0 & g_l(\nu) \end{bmatrix}.$$

We will now discuss the information capacity for the spatio-temporal channel developed above. The following analysis assumes that the noise $\mathbf{n}(k)$ is additive white Gaussian noise (AWGN) with covariance $\sigma^2\mathbf{I}_{\nu+1}$. Each channel use consists of an N symbol burst transmission and the total average power radiated from all antennas and all time samples is constrained to less than a constant.

Write the singular value decomposition (SVD) of the channel matrix as $\mathbf{H}(k)=\mathbf{V}_H(k)\Lambda_H(k)\mathbf{U}_H^*(k)$, with the n^{th} singular value denoted $\lambda_{H,n}(k)$. Write the spatio-temporal covariance matrix for $\mathbf{z}(k)$ for block index k as $\mathbf{R}_Z(k)$ with eigenvalue decomposition $\mathbf{R}_Z(k)=\mathbf{V}_Z(k)\Lambda_Z(k)\mathbf{U}_Z^*(k)$, and eigenvalues $\lambda_{Z,n}(k)$.

It can be demonstrated that, if the case where the instantaneous channel state information is known at both the transmitter and receiver, then the information capacity for

the time-varying discrete-time spatio-temporal communication channel defined above is given by

$$C = E\left(\sum_{n=1}^{K} \log\left(1 + \frac{\lambda_{Z,n}(k)\,|\lambda_{H,n}(k)|^2}{\sigma^2}\right)\right),$$

where $\lambda_{Z,n}(k)$ is given by the spatio-temporal water-filling solution, $E(\cdot)$ is the expectation operator, and K is the number of finite amplitude singular values in $\mathbf{H}(k)$.

For the case where only the receiver has instantaneous channel state information, it is not possible to adapt the transmitter for each block. Nevertheless, it is possible to find the time invariant transmitter covariance which maximizes the capacity for the worst case channel possibilities. For any given transmitted signal covariance matrix $\mathbf{R}_Z$, the worst case channel would place all of the time average energy in the rank 1 subspace defined by the smallest eigendirection in $\mathbf{R}_Z$. This game theoretic problem leads to a spatially uncorrelated transmitter covariance solution $\mathbf{R}_Z = \frac{P_T}{M_T}\mathbf{I}_{M_T}$, where P_T is the maximum average block transmission power. This transmitter covariance is used for completely unknown point to point channels and broadcast channels. For this case of unknown CSI at the transmitter, it can be shown that a white space-time transmission distribution gives a channel capacity

$$C = E\left(\sum_{n=1}^{K} \log\left(1 + \frac{P_T\,|\lambda_{H,n}(k)|^2}{M_T\sigma^2}\right)\right).$$

By analyzing the ranks of the matrices in the path decomposition of the time varying channel $\mathbf{H}(t)$, it can be demonstrated that the maximum number of finite amplitude parallel spatio-temporal channel dimensions, K, that can be created to communicate over the far field time-varying channel

defined above is equal to min{ $N \cdot L$, $(N+\nu) \cdot M_R$, $N \cdot M_T$ }, where L is the number of multipath components. Thus, multipath is an advantage in far-field MIMO channels. If the multipath is large ($L \gg 1$), the capacity can be multiplied by adding antennas to both sides of the radio link. This capacity improvement occurs with no penalty in average radiated power or frequency bandwidth because the number of parallel channel dimensions is increased. In practice, an adaptive antenna array base station, such as that described by Barratt et al., is modified to implement a coding scheme, as described below, which exploits these additional dimensions. In particular, a signal processor is designed to perform a spatio-temporal transform of information signals in accordance with the above equations so that they may be transmitted through the independent parallel subchannels and decoded by the subscriber.

In constant or slowly varying channels, it is often possible to send training sequences to the receiver and communicate channel state information (CSI) back to the transmitter in a manner that accurately tracks time variations. In such cases, the transmitter can implement a coding solution which approaches the theoretical capacity limits. The MIMO communication problem becomes more difficult when the channel fades rapidly in time as is the case with portable wireless communication in the microwave frequency bands. It then becomes impractical to feed back CSI from the receiver to the transmitter due to the information bandwidth required to update the channel state in real time. It is highly desirable in such cases to have a channel coding technique that exploits the spatial dimension of the MIMO problem without requiring any CSI at the transmitter. Such a coding technique has been devised by the present inventors and is described in detail below.

Given the time-varying channel defined by $\mathbf{H}(t)$, it is theoretically possible to create a coding system consisting of

a spatio-temporal encoder, and a spatio-temporal maximum likelihood decoder. The obvious difficulty with such a system is the complexity of the decoder. The complexity of the spatio-temporal decoder can be greatly reduced, however, by using a matrix orthogonal frequency division multiplexing (MOFDM) structure according to the present invention. The complexity reduction occurs because inter-symbol interference (ISI) is eliminated from each OFDM sub-channel.

The MOFDM channel structure is derived under the assumption that the channel is block time invariant over a block of N+2ν symbol periods. Under this assumption, the channel fading matrix $\mathfrak{B}_l(k)$ can be replaced by the scalar fading variable $\beta_l(k)$. Note that the block time invariant assumption is reasonable provided that the block duration $(N+2\nu)T \ll \Delta_\beta$, where Δ_β is the correlation interval for the channel fading variable. (The correlation interval is defined here as the time period required for the fading parameter time-autocorrelation function to decrese to some fraction of the zero-shift value.)

For MOFDM, N data symbols are transmitted during each channel usage. However, a cyclic prefix is added to the data so that the last ν data symbols form a preample to the N data symbol message block. By discarding the first and last ν data symbols at the receiver and retaining only N time samples at the channel output, the new MIMO channel $\hat{\mathbf{H}}(k)$ has a block cyclic structure:

$$\hat{\mathbf{H}}(k) = \sum_{l=1}^{L} \beta_l(k) \begin{bmatrix} a_{R,1}(\theta_{R,l})\mathbf{I} \\ \vdots \\ a_{R,M_R}(\theta_{R,l})\mathbf{I} \end{bmatrix} \hat{\mathbf{G}}_l \left[a_{T,1}(\theta_{T,l})\mathbf{I} \quad \ldots \quad a_{T,M_T}(\theta_{T,l})\mathbf{I} \right].$$

where the cyclic pulse shaping matrix $\hat{\mathbf{G}}(k)$ is given by

$$\hat{\mathbf{G}}_l = \begin{bmatrix} g_l(0) & 0 & \cdots & 0 & g_l(\nu) & \cdots & g_l(1) \\ \vdots & \ddots & \ddots & & \ddots & \ddots & \\ g_l(\nu-1) & \cdots & g_l(0) & 0 & \cdots & 0 & g_l(\nu) \\ g_l(\nu) & g_l(\nu-1) & \cdots & g_l(0) & 0 & \cdots & 0 \\ & & & \ddots & \ddots & & \\ 0 & \cdots & 0 & g_l(\nu) & g_l(\nu-1) & \cdots & g_l(0) \end{bmatrix}.$$

The MOFDM channel model can now be derived as follows. First post multiply $\hat{\mathbf{H}}(k)$ with the $N \cdot M_T \times N \cdot M_T$ block diagonal inverse discrete Fourier transform (IDFT) matrix $\mathbf{F}^{*(M_T)}$ where each diagonal block is the unitary $N \times N$ IDFT matrix $\mathbf{F}^*$. The next step is to premultiply by a similar $N \cdot M_R \times N \cdot M_R$ block diagonal DFT matrix $\mathbf{F}^{(M_R)}$ where the diagonal submatrices $\mathbf{F}$ are $N \times N$ DFT matrices. Pre- and post-multiplication by permutation matrices $\mathbf{P}_R$ and $\mathbf{P}_T$ then gives the decomposition of the channel into discrete discrete Fourier transform (DFT) frequency domain sub-channels $\mathcal{H}_n(k)$, as follows:

$$\begin{aligned} \mathcal{H}(k) &= \sqrt{(N)}\,\mathbf{P}_R \mathbf{F}^{(M_R)} \hat{\mathbf{H}}(k) \mathbf{F}^{*(M_T)} \mathbf{P}_T \\ &= \begin{pmatrix} \mathcal{H}_1(k) & & 0 \\ & \ddots & \\ 0 & & \mathcal{H}_N(k) \end{pmatrix} \end{aligned}$$

Each channel $\mathcal{H}_n(k)$ is independent of the other frequency domain sub-channels. Just as in the case of scalar OFDM, the cyclic prefix allows the large time domain channel to be decomposed into many smaller parallel frequency domain channels. The received vector signal $\mathcal{X}_n(k)$ for each frequency domain spatial sub-channel can then be expressed as

$$\mathcal{X}_n(k) = \mathcal{H}_n(k)\mathcal{Z}_n(k) + \mathcal{N}_n(k),$$

where $\mathcal{Z}_n(k)$ is the subchannel transmitted signal and $\mathcal{N}_n(k)$ is the subchannel noise. A system architecture implementing this channel structure is shown in FIG. 7A.

The spatial sub-channels can also be expressed as

$$\mathcal{H}_n(k) = \sum_{l=1}^{L} \beta_l(k)\ \mathcal{G}_{l,n}\ \mathbf{a}_{R,l}\ \mathbf{a}_{T,l}^{T}$$

where $\mathcal{G}_{l,n}$ is the DFT of the sequence $\{g_l(k)\}$ evaluated at DFT index n. At each frequency index, the DMMT channel is due to a weighted sum over L rank-1 outer products of the frequency-invariant receive and transmit array response vectors. The weighting is determined by the frequency invariant path fading values and the Fourier transform of the delayed pulse shaping function. This reveals a highly structured nature for the time varying space-frequency channel spectrum.

In the case of rapidly fading channels where CSI is not available at the transmitter, the appropriate transmitter distribution is a spatially and temporally white transmitter sequence. Nevertheless, as seen from the above channel decomposition, the use of cyclic signal structures allows the determination of a channel structure that can still be exploited to improve capacity. Therefore, a practical subchannel coding method which approximates a white distribution is desired. Although many variations are possible, the following description is focused on a particularly simple strategy involving a one dimensional trellis coding structure.

In MOFDM, a space-frequency code is transmitted. Given M_T transmitting antenna elements and the MOFDM subchannel decomposition of $\mathcal{H}(k)$, a codeword sequence $\mathbf{c}^{(j)}$ of constraint length $N_c^{(j)}$ can be viewed as q spatial vector code segments transmitted in each of $q = \frac{|\mathbf{c}^{(j)}|}{M_T}$ frequency bins where $|\mathbf{c}^{(j)}|$ is the length of the code sequence. In this embodiment, an information signal b(k) is converted into a code sequence $\mathbf{c}^{(j)}$ by a one dimensional trellis encoder, as shown in FIG. 8. Code

segments of length M_T form a spatial vector code $\mathbf{c}_n^{(j)}$ for a single MOFDM frequency bin indexed by n. After training symbols are injected, frequency domain interleaving is performed by an interleaver in order to distribute consecutive spatial vector code segments among well separated frequency bins. Interleaving allows the system to exploit the frequency diversity of the channel while the spatial coding is a form of spatial diversity.

Each of the M_T symbols in a given spatial vector code segment for a given frequency bin are transmitted from one of the antennas. At the receiver, a matched frequency de-interleaver transforms the space-frequency sequence back into a serial signal stream. A tilde, ~, above a variable is used to denote the signal sequence before interleaving and after de-interleaving operations. Define

$$\mathbf{c}^{(j)} = [\ c_0^{(j)}, \ldots, c_{qM_T-1}^{(j)}\ ]^T$$

as the trellis encoder symbol sequence codeword of length qM_T indexed by j. Further define

$$\tilde{\mathfrak{X}}^{(q)}(k) = [\ \tilde{\mathfrak{X}}_{lM_R}(k),\ \ldots,\ \tilde{\mathfrak{X}}_{lM_R+qM_T-1}(k)\ ]^T$$

as the received de-interleaved signal sequence due to the transmitted code $\mathbf{c}^{(j)}$ where lM_R is the beginning index for the received sequence of length qM_R spanning q space-frequency subchannels. The output sequence due to codeword $\mathbf{c}^{(j)}$ can now be written as

$$\tilde{\mathfrak{X}}^{(q)}(k) = \sqrt{\frac{P_T}{M_T}}\ \tilde{\mathfrak{H}}^{(q)}(k)\mathbf{c}^{(j)} + \tilde{\mathfrak{N}}^{(q)}(k)$$

where

$$\mathfrak{H}^{(q)}(k) = \begin{pmatrix} \tilde{\mathfrak{H}}_{l}(k) & & 0 \\ & \ddots & \\ 0 & & \tilde{\mathfrak{H}}_{l+q}(k) \end{pmatrix}$$

and

$$\sqrt{\frac{P_T}{M_T}}\,\mathbf{c}^{(j)} = \begin{pmatrix} \tilde{\mathfrak{Z}}_{lM_T}(k) \\ \vdots \\ \tilde{\mathfrak{Z}}_{l+qM_T-1}(k) \end{pmatrix}.$$

The additive noise term $\tilde{\mathfrak{N}}^{(q)}(k)$ is still white after the MOFDM channel operations.

For a given spatio-temporal symbol code set

$$\mathbf{C} = \{\ \mathbf{c}^{(1)}, \ldots,\ \mathbf{c}^{(J)}\}$$

the maximum likelihood detector is given by

$$\hat{\mathbf{c}} = \arg \max_{\mathbf{c}(j)}\ P(\mathbf{c}^{(j)} | \tilde{\mathfrak{X}}^{(q)}(k)).$$

FIG. 7B shows such a detector which is used to generate the recovered information stream, $\hat{b}(k)$. Given that the receiver noise present in each space-frequency sub-channel is multivariate AWGN, it is known that the equivalent decoder optimization is

$$\hat{\mathbf{c}} = \arg \min_{\mathbf{c}(j)}\ \left|\left|\sqrt{\frac{P_T}{M_T}}\ \tilde{\mathfrak{H}}^{(q)}(k)\mathbf{c}^{(j)} - \tilde{\mathfrak{X}}^{(q)}(k)\ =\ \right|\right|_2^2.$$

This equation can be solved efficiently using a vector Viterbi detector similar to that used in ISI channels. The main difference here is that while there is correlation in the received spatial code segment in each frequency bin, the information across frequency bins is uncorrelated. This allows the metric computation to be pruned back to the number

of states in the trellis encoder at the beginning of each new spatial code segment hypothesis test. It is undesirable for the encoder to posses parallel transitions because this reduces the diversity order of the code to one. Therefore, all of the encoder input bits are fed to the convolutional encoder with rate r and there are there is only one member in each of the cosets.

The inventors have discovered that, given a random Rayleigh channel process with uncorrelated spatial fading and perfect frequency domain interleaving and any code set **C**, the upper bound on the average bit error rate for a $1 \times m$ SIMO channel is larger than the bound for a $M \times mM$ MIMO channel, even though the later transmits data at M times the rate of the former. This remarkable fact reveals some very interesting behavior for the proposed MIMO channel coding structure. Although the data rate for the $M_R = M = M_T$ MIMO channel goes up linearly with M, the probability of error bound is smaller than that for the SISO channel. While the transmitter power for each spatial symbol must be reduced as the number of antennas and spatial sequences are increased, the length of the spatial code segment error vector $\mathbf{e}_n(j1, j2)$ also increases to offset the transmitter power reduction. In addition, while the frequency diversity due to the number of frequency bins spanned by the code error sequence is reduced as M increases, the denominator exponent increases due to spatial diversity. Thus, as M increases, the effects of frequency diversity are replaced by spatial diversity. Furthermore, it is clear that the MIMO system can benefit from additional spatial diversity by setting $M_R > M_T$. The m-order spatial diversity error performance of a $1 \times m$ SIMO channel can be achieved with an $M \times mM$ MIMO channel which will again achieve M times the data rate of the SIMO channel while maintaining lower error probability.

An alternative code design metric for the spatio-temporal coding structure presented in relation to FIGS. 7A and 7B is

suggested by observing that the correct error sequence metric for code design is clearly the product of Euclidean distances for each of the M_T length spatial error vector segments in the error event sequences. This metric is strikingly similar to periodic product distance metrics that are known from other contexts.

An important aspect of the present invention is channel estimation. In fast fading channels, overhead penalties for conventional multi carrier training techniques can be severe. A large number of sub-channels N is desired so that cyclic prefix overhead is minimized. Large N corresponds to long OFDM symbol duration. Long symbol duration, in turn, requires short intervals between training. In conventional channel training procedures, an entire OFDM symbol is dedicated to training, and several data symbols are inserted between training symbols. Thus, a trade-off exists between cyclic prefix and training overhead with conventional channel estimation techniques.

Furthermore, in burst-mode transmission applications such as wireless ATM, if the average data rate for a virtual circuit is low, then the time between ATM packets can be large. In such cases, it is not feasible to use an entire DMT symbol for training since the channel can change substantially between training symbols. What is needed is a training strategy that allows "instantaneous updates" for the channel estimation algorithm. The present inventors have developed a training approach and channel estimation algorithm which injects training information along with data into each OFDM symbol. The channel estimation algorithm exploits the correlation properties of the time varying wireless channel to estimate the spatial channel for each MOFDM frequency domain sub-channel.

Imperfect channel knowledge can have an impact on error probability, and channel estimation noise in the receiver will

limit the performance of a spatio-temporal coding system. The inventors have discovered that the effect of channel estimation errors can be modeled as an increase in the effective noise variance. This noise variance increase is an interesting function of the time varying channel correlation function, the portable velocity, the average channel SNR and the design of the channel estimation algorithm. Thus, proper design of the channel estimator is critical for low error probability communication.

In all that follows, we again invoke the spatially uncorrelated Rayleigh fading condition. Although the spatial fading is uncorrelated, there is correlation in the OFDM frequency and time domains which we wish to exploit. The correlation in the frequency domain arises from the delay limited nature of the channel impulse response. The correlation in the time domain fading arises from the band limited Doppler shifts experienced by physical objects which move in the vicinity of the portable. We desire a channel estimation algorithm that exploits these correlation properties in an optimal manner.

To estimate the matrix channel that exists at a given OFDM frequency index, note that we can simply estimate the M_T column vectors of dimension $1 \times M_R$. Given that the column vectors are assumed to fade independently, an optimal training strategy is to transmit M_T different training sequences from each transmitter antenna and estimate the resulting column vectors without considering the information received during training from the other transmitter antennas. In addition, the uncorrelated spatial fading assumption allows each of the scalar elements in a given channel column vector to be estimated independently. Thus, with M_T training sequences transmitted independently from each antenna, we can estimate M_R independent frequency domain scalar channel entries. Thus, the focus is on a SISO training strategy for the frequency domain sub-channels that exist between one transmitter antenna

and one receiver antenna. The SISO estimation algorithm is directly generalized to the MIMO case by stacking SISO estimates from each receiver antenna into columns and exploiting the cyclic shift properties of the DFT.

Our SISO channel estimation strategy will be to transmit training symbols in several equally spaced OFDM sub-channels with data embedded between training symbols. For a discrete time channel which is delay limited to $\nu+1$ finite impulse response terms, $\nu+1$ OFDM training sub-channels are sufficient to construct an estimate of all N sub-channels.

A SISO OFDM channel estimation algorithm is now described. The channel frequency domain training symbol sequence is defined as

$$\mathcal{Z}_T = \mathrm{diag}\left[\mathcal{Z}_0, \mathcal{Z}_{\frac{N}{\nu+1}}, \ldots, \mathcal{Z}_{\frac{\nu N}{\nu+1}}\right].$$

By construction, $\mathcal{Z}_T\mathcal{Z}_T^* = P_T\mathbf{I}_{\nu+1}$.

The channel estimation procedure is as follows.

1. Given n_1 past measurements, the present measurement, and n_2 future measurements of the frequency-domain training sub-channel outputs, form n_1+n_2+1 measurements of the time varying channel impulse response vector $\tilde{\mathbf{h}}^{(\nu+1)}(k)$ by dividing the received known training symbols into the outputs and then performing the IDFT operation, i.e.

$$\tilde{\mathbf{h}}^{(\nu+1)}(k) = \sqrt{\frac{\nu+1}{N}}\,\mathbf{F}_{\nu+1}^*\mathcal{Z}_T^{-1}\mathfrak{X}_T^{\nu+1}(k),$$

where $\mathfrak{X}_T^{\nu+1}(k) = \left[\mathfrak{X}_0(k), \mathfrak{X}_{\frac{N}{\nu+1}}(k), \ldots, \mathfrak{X}_{\frac{\nu N}{\nu+1}}(k)\right]^T$ and $\mathbf{F}_{\nu+1}$ is the $\nu+1$ point DFT matrix.

2. Form the channel impulse response estimate $\hat{\mathbf{h}}^{(\nu+1)}(k)$ by applying an optimal linear MMSE estimation filter independently to each of the impulse response measurements $\tilde{\mathbf{h}}^{(\nu+1)}(k)$, i.e.

$$\hat{\mathbf{h}}^{\nu+1}(k) = \left[\mathbf{w}_h^{*} \otimes \mathbf{I}_{\nu+1}\right]\begin{bmatrix}\tilde{\mathbf{h}}^{\nu+1}(k-n_1)\\ \vdots \\ \tilde{\mathbf{h}}^{\nu+1}(k-n_2)\end{bmatrix},$$

where $\otimes$ denotes the Kronecker product and $\mathbf{w}_h$ is the scalar Weiner filter for $\hat{\mathbf{h}}^{(\nu+1)}(k)$.

3. Form the complete OFDM channel estimate by zero-padding the channel impulse response estimate and performing an N-point FFT, i.e.

$$\hat{\mathfrak{H}}^{(N)} = \mathbf{F}_N\ [\ \hat{\mathbf{h}}^{(\nu+1)}(k),\ 0,\ \ldots,\ 0\ ]^T.$$

Given the iid fading assumption on the channel impulse response terms, the above channel estimation algorithm is optimal within the class of linear MMSE estimators.

To extend the preceding scalar channel analysis methods to estimate the OFDM matrix subchannels, the following procedure is employed. Rather than transmitting $\nu+1$ training symbols spaced by $\frac{N}{\nu+1}$ sub-channels, we transmit $\nu+1$ frequency domain sequences, each of length M_T. This training scheme is illustrated in Table 1 where the notation T(n) represents training symbol n and D(k) represents data symbol k.

Table 1

FFT bin	Content
0	T(0)
:	:
M - 1	T(M-1)
M	D(0)
:	:
N/(ν+1) - 1	D(N/(ν+1) - M - 1)
:	:
νN/(ν+1)	T(νM)
:	:
νN/(ν+1) + M - 1	T(M(ν+1) - 1)
νN/(ν+1) + M	D((ν-1)(N/(ν+1)-M))
:	:
N - 1	D(νN/(ν+1)-νM - 1)

In each of the M_T long training sequences, the first symbol is transmitted from the first antenna, the second symbol from the second antenna, and so on. The first column in the frequency domain sub-channel matrix response is then estimated by performing the scalar channel estimation algorithm on each of the M_R antenna outputs associated with the $\nu+1$ subchannels which appear first in the M_T long training sequences, and stacking the scalar estimates into a vector. The other columns of the matrix channel are estimated in a similar manner, with the exception that the final frequency domain estimates $\hat{\mathfrak{H}}(k)$ obtained from the channel estimation algorithm are cyclic-shifted to account for the frequency sub-channel offset for each transmitter antenna training sequence.

Using this technique, for a complex $M_T \times M_R$ DMT channel, only $M_T(\nu+1)$ DMT sub-channels are required for training. The channel overhead loss due to training and the cyclic prefix is

then $\frac{M_T(v+1)+v}{N+v}$. This training technique only requires FFTs and FIR channel estimation filters to implement.

Among the various applications of the present invention, one of particular utility is a wideband wireless ATM local area network for a campus environment. The transmitted digital symbol rate is 10 MHz. The portable terminals are mobile with a maximum velocity of 70 miles per hour. The RF carrier frequency is 5.2 GHz. This application is extremely challenging for conventional equalizer based communication structures due to the large delay spread and extremely high Doppler frequency (+/- 540 Hz). The Doppler shift also makes conventional CDMA approaches difficult due to the required power control loop bandwidth. For these reasons, the application is an ideal candidate for MOFDM. In one embodiment, such a MOFDM system may have 3 transmitter antennas and either 3 or 6 receiver antennas.

Thus, it will be clear to one skilled in the art that the above embodiment may be altered in many ways without departing from the scope of the invention. Accordingly, the scope of the invention should be determined by the following claims and their legal equivalents.

CLAIMS

What is claimed is:

1. A method of digital wireless communication between a base station and a subscriber unit, the method comprising:
space-frequency encoding a plurality of information signals into a sequence of transmitted signal vectors, wherein the transmitted signal vectors have M_T complex valued components and are selected to send the information signals over the a collection of independent spatial subchannels;
transmitting the sequence of transmitted signal vectors over a spatial channel coupling an array of M_T antenna elements at the base station with an array of M_R antenna elements at the subscriber unit;
receiving a sequence of received signal vectors at the subscriber unit, wherein the received signal vectors have M_R complex valued components; and
performing a space-frequency maximum likelihood detection upon the received signal vectors to recover the information signals.

2. The method of claim 1 wherein the encoding step comprises performing matrix orthogonal frequency division multiplexing of the information signals.

3. The method of claim 1 further comprising the step of injecting training sequences into the information signals.

4. The method of claim 1 further comprising adding cyclic prefixes to the coded signal prior to the transmitting step.

5. The method of claim 1 wherein the encoding step is performed in accordance with a spatio-temporal subchannel decomposition of the channel into independent modes.

6. A digital wireless communication system comprising:
a base station comprising a base station antenna array and a base station signal processor coupled to the base station antenna array;
a subscriber unit comprising a subscriber antenna array coupled through a wireless channel to the base station antenna array and a subscriber signal processor coupled to the subscriber antenna array;
wherein the base station signal processor encodes downlink signal information by matrix orthogonal frequency division multiplexing the signal information; and
wherein the subscriber signal processor decodes the downlink signal information by vector maximum likelihood detection and space-frequency matrix channel estimation.

7. The system of claim 6 wherein the base station signal processor performs interleaving of the signal information and wherein the subscriber signal processor performs de-interleaving.

8. The system of claim 6 wherein the base station signal processor performs trellis encoding of the signal information.

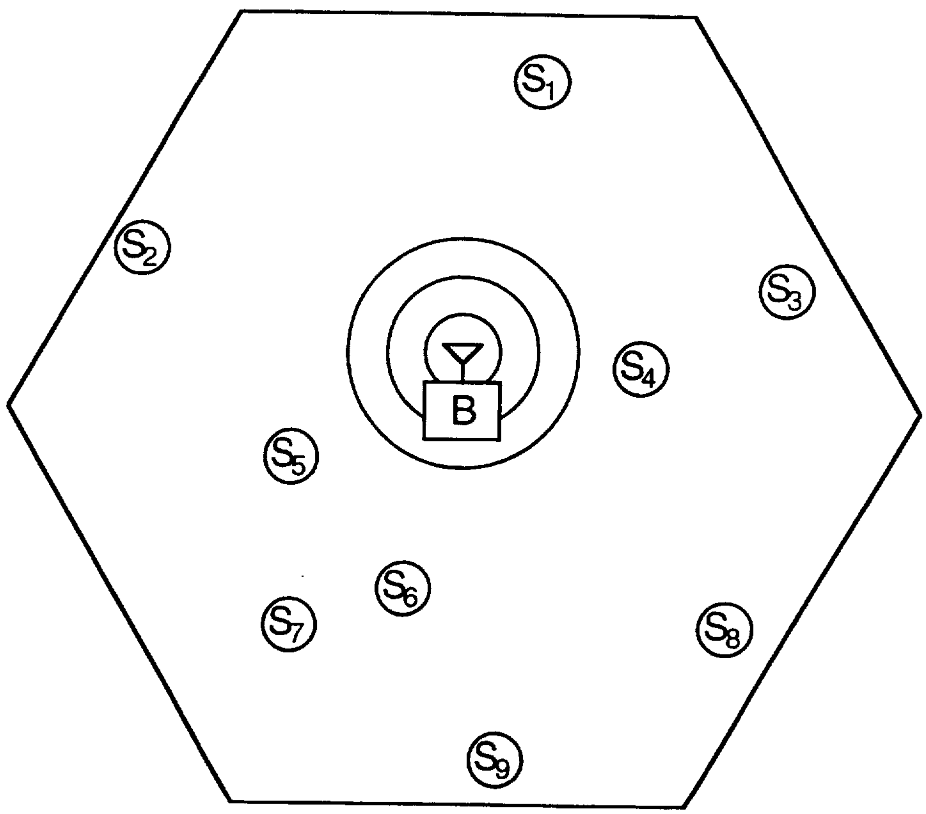


FIG. 1
(PRIOR ART)

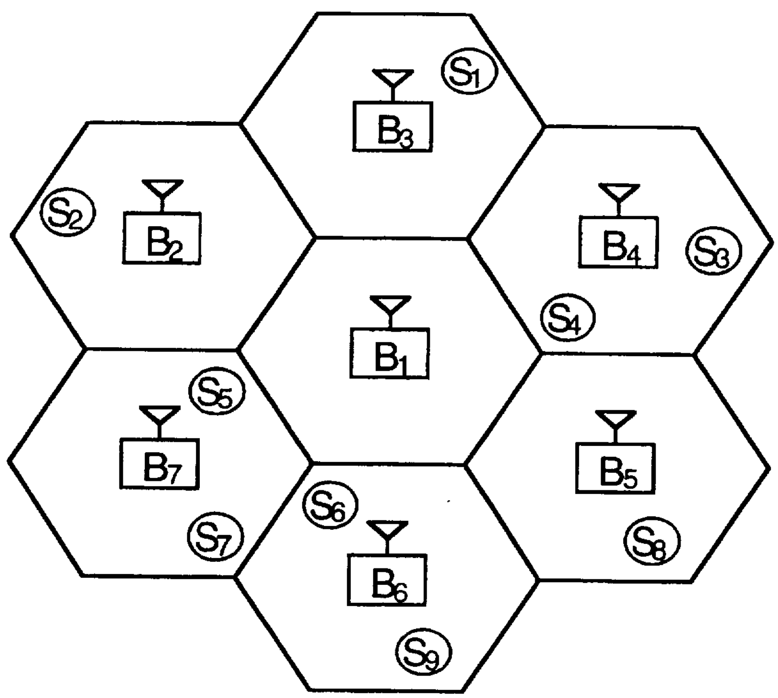


FIG. 2
(PRIOR ART)

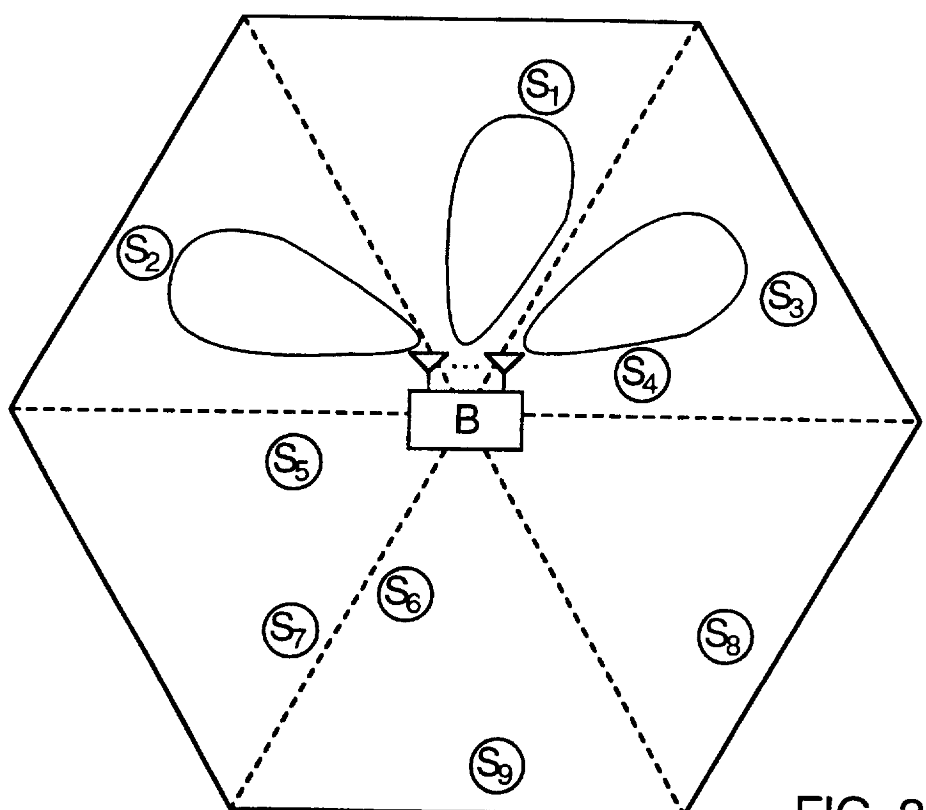


FIG. 3
(PRIOR ART)

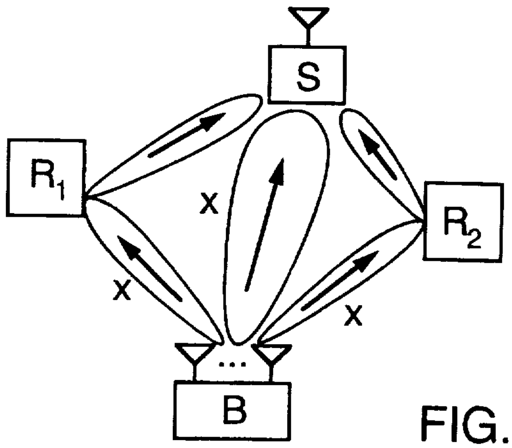


FIG. 4A
(PRIOR ART)

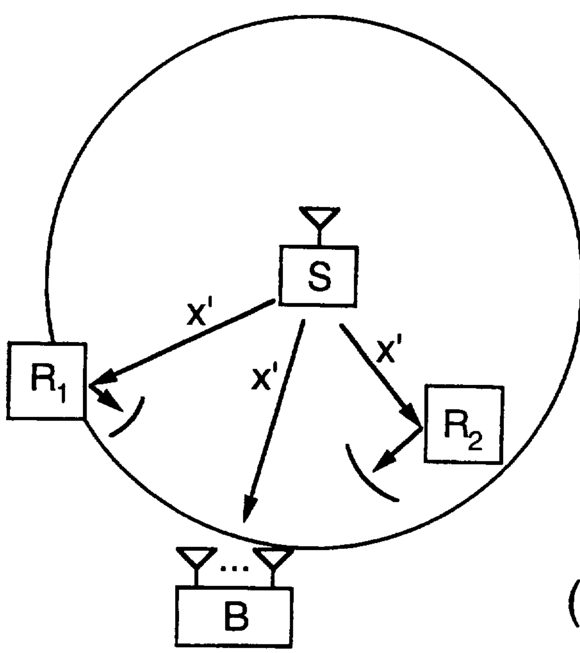


FIG. 4B
(PRIOR ART)

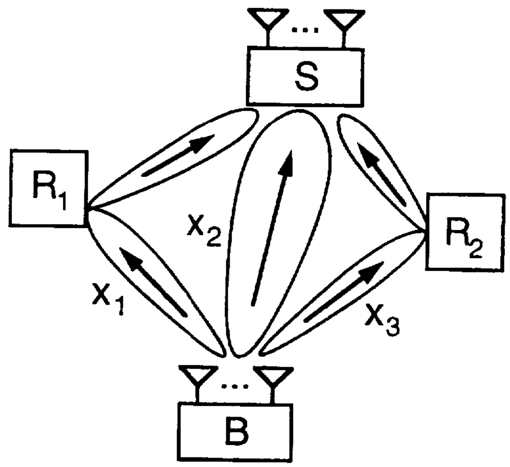


FIG. 5A

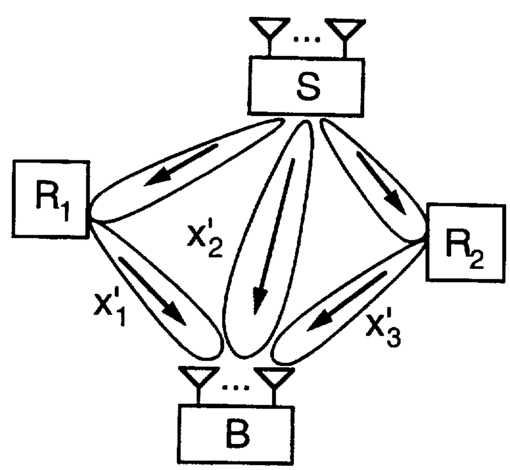
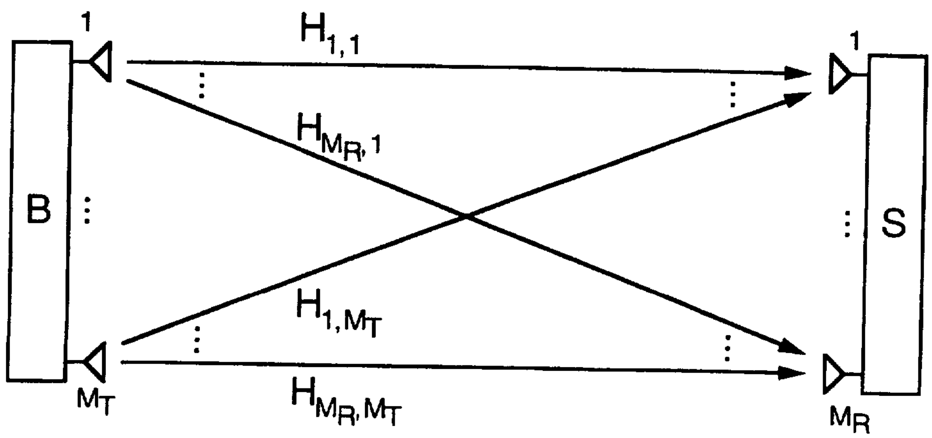
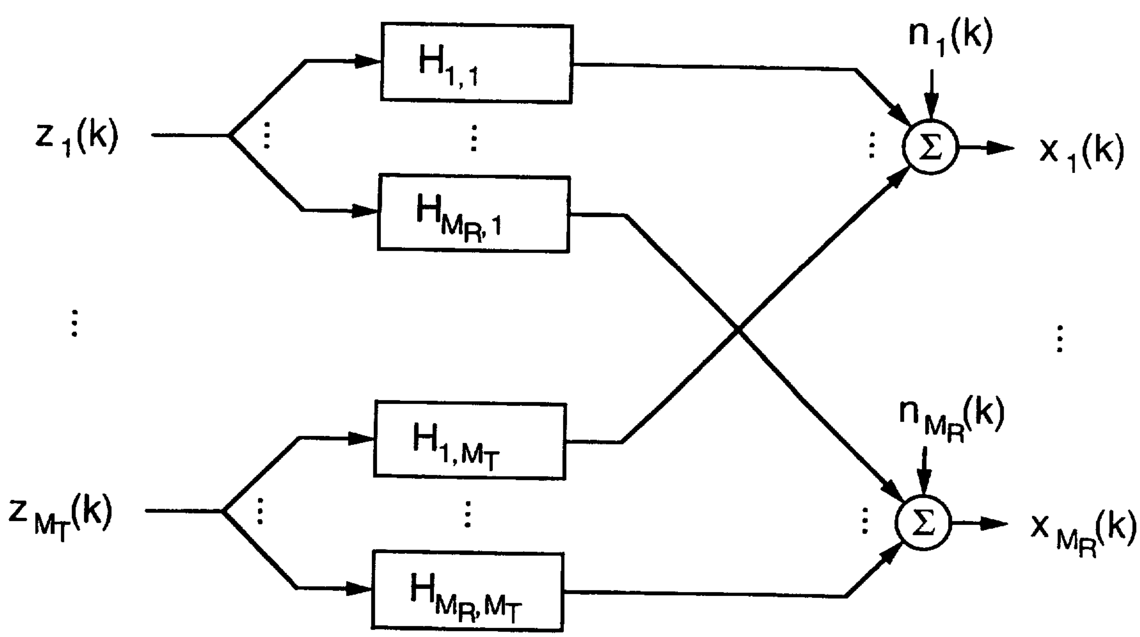


FIG. 5B



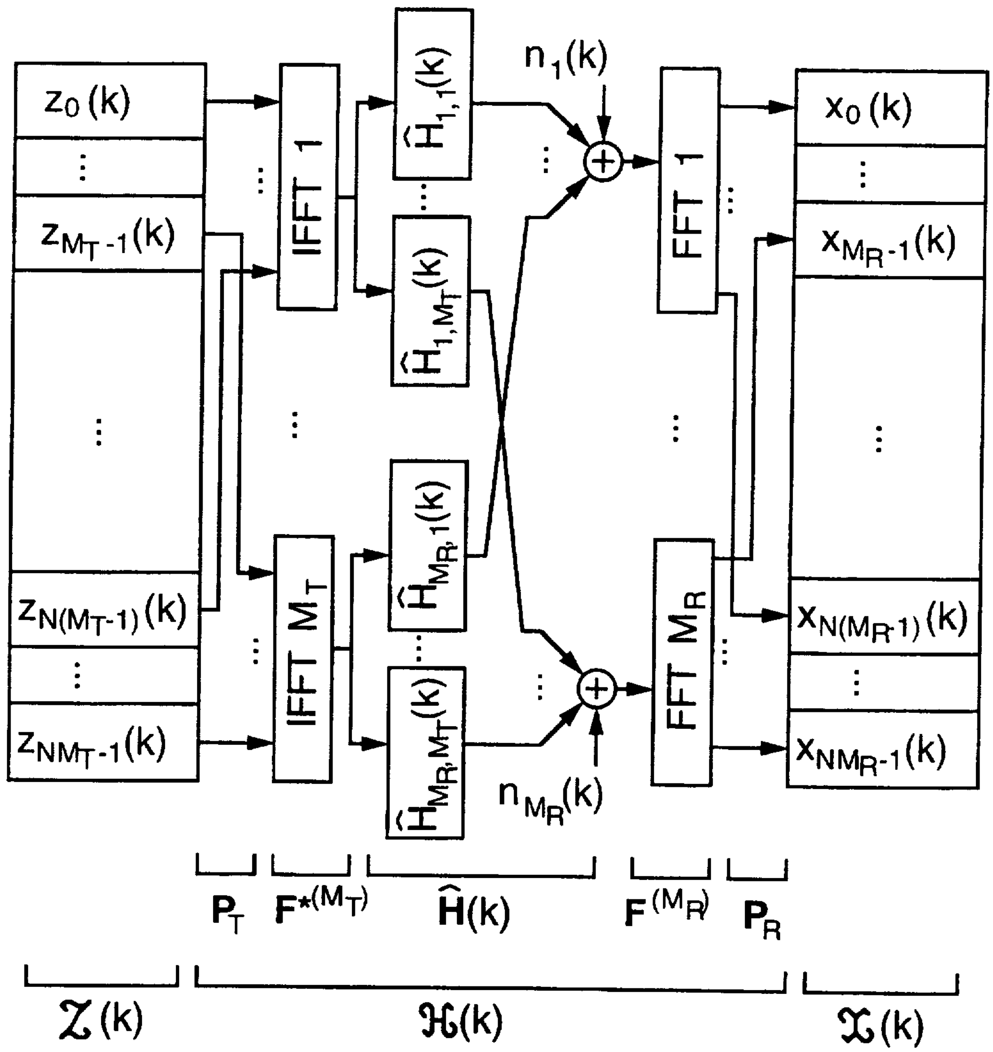
1
H1,1
1
HMR,1
B
S
H1,MT
MT
HMR,MT
MR

FIG. 6A



H1,1
n1(k)
z1(k)
Σ
x1(k)
HMR,1
H1,MT
nMR(k)
zMT(k)
Σ
xMR(k)
HMR,MT

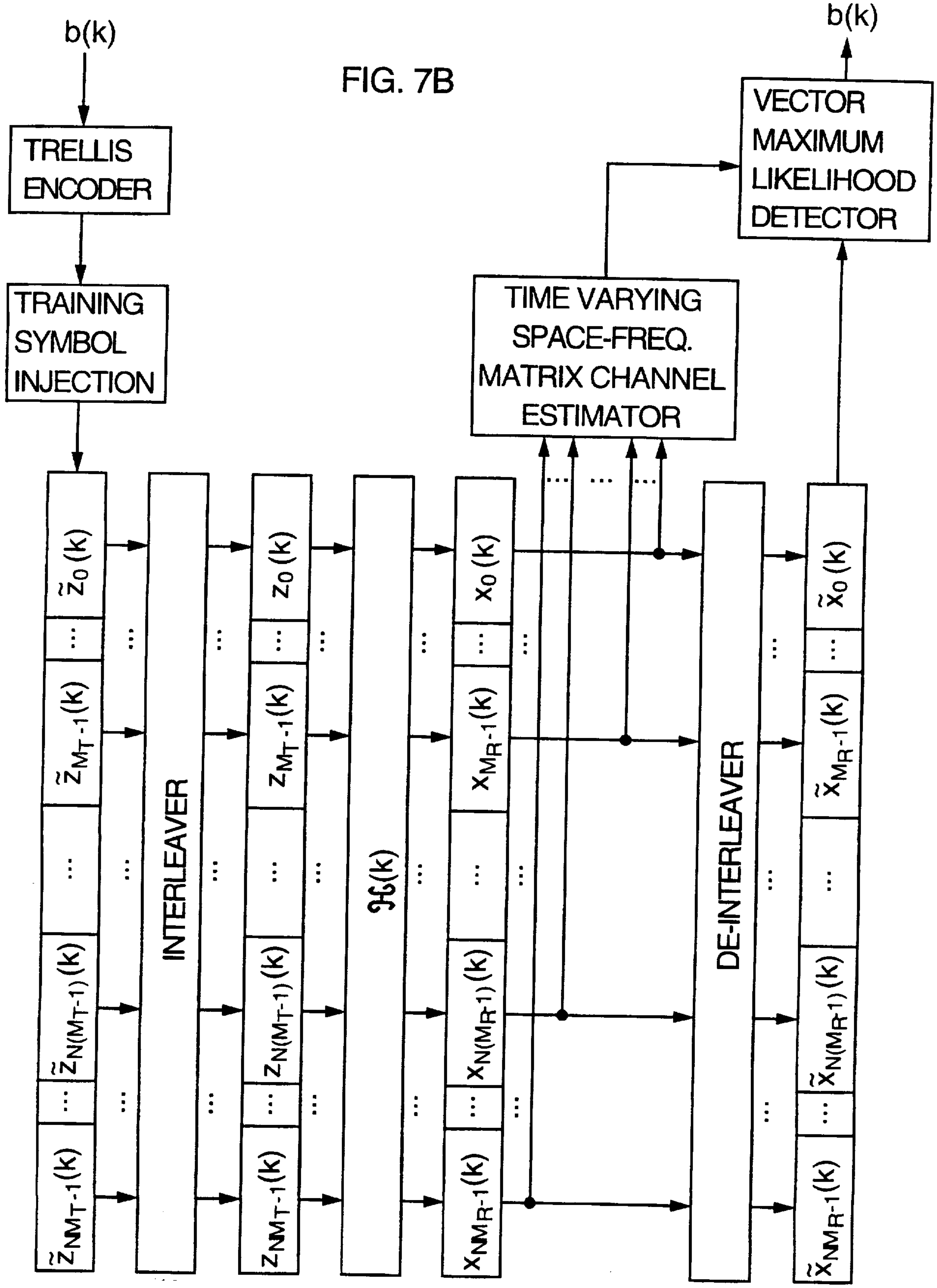
FIG. 6B



$z_0(k)$
$z_{M_T-1}(k)$
$z_{N(M_T-1)}(k)$
$z_{NM_T-1}(k)$
IFFT 1
IFFT M_T
$\hat{H}_{1,1}(k)$
$\hat{H}_{1,M_T}(k)$
$\hat{H}_{M_R,1}(k)$
$\hat{H}_{M_R,M_T}(k)$
$n_1(k)$
$n_{M_R}(k)$
FFT 1
FFT M_R
$x_0(k)$
$x_{M_R-1}(k)$
$x_{N(M_R-1)}(k)$
$x_{NM_R-1}(k)$
$\mathbf{P}_T$
$\mathbf{F}^{*(M_T)}$
$\hat{\mathbf{H}}(k)$
$\mathbf{F}^{(M_R)}$
$\mathbf{P}_R$
$\mathfrak{Z}(k)$
$\mathfrak{H}(k)$
$\mathfrak{X}(k)$

FIG. 7A

FIG. 7B


b(k)
TRELLIS ENCODER
TRAINING SYMBOL INJECTION
INTERLEAVER
$\mathcal{H}(k)$
TIME VARYING SPACE-FREQ. MATRIX CHANNEL ESTIMATOR
DE-INTERLEAVER
VECTOR MAXIMUM LIKELIHOOD DETECTOR
$\hat{b}(k)$
$\tilde{z}_0(k)$
$\tilde{z}_{M_T-1}(k)$
$\tilde{z}_{N(M_T-1)}(k)$
$\tilde{z}_{NM_T-1}(k)$
$z_0(k)$
$z_{M_T-1}(k)$
$z_{N(M_T-1)}(k)$
$z_{NM_T-1}(k)$
$x_0(k)$
$x_{M_R-1}(k)$
$x_{N(M_R-1)}(k)$
$x_{NM_R-1}(k)$
$\tilde{x}_0(k)$
$\tilde{x}_{M_R-1}(k)$
$\tilde{x}_{N(M_R-1)}(k)$
$\tilde{x}_{NM_R-1}(k)$

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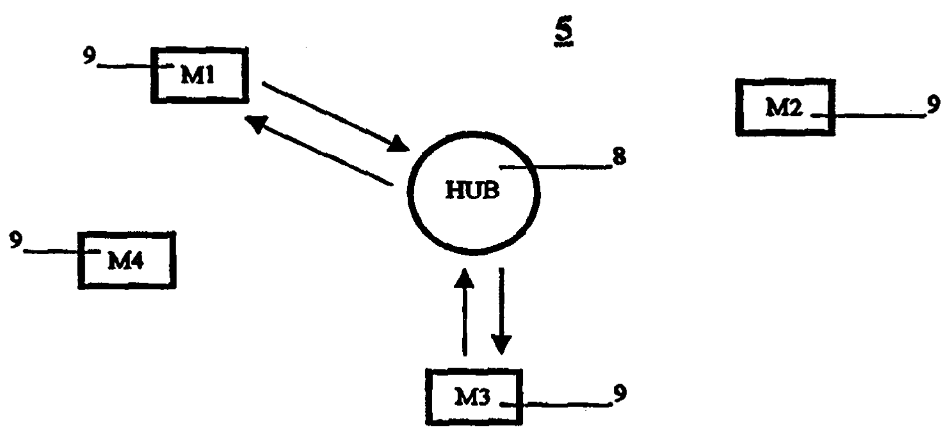

(57) Abstract

A method for controlling communications between a hub and a plurality of distributed stations over a medium is disclosed. The method comprises the steps of a method for controlling communications access between a hub (8) and a plurality of distributed stations (M1–M7) over a medium, the method comprising the steps of (a) allocating a plurality of channels for data communications between the station (M1–M7) and the hub (8), the number of channels being at least equal to the number of stations, (M1–M7) and each station owning at least one channel, each channel being varyingly in one of an empty–, a reserved–, or an owner–state, and whereby (i) the empty–state provides a channel to which any station (M1–M7) can have access; (ii) the reserved–state provides a channel to which a station (M1–M7) having made a reservation with the hub (8), but not owning the channel, can have access; and (iii) the owner–state provides a channel to which only the owning station (M1–M7) has access; and (b) re–allocating the respective state and/or the number of channels over time on the basis of each station's data requirements.

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MEDIUM ACCESS CONTROL PROTOCOL FOR DATA COMMUNICATIONS

Field of the Invention

This invention relates to the field of data communications, and to methods and apparatus to implement a Medium Access Control (MAC) protocol therefor. The invention has particular (but not exclusive) application in wireless communications environments such as μ-wave, mm-wave or infra-red. The term "data communications" is to be understood in its broadest sense to include data *per se*, and forms such as voice and video.

Background of the Invention

For discussion purposes, reference will be made to wireless MAC protocols, however it should be understood that the invention is equally applicable to cabled (ie. wire and optical fibre) and wireless data communications alike.

A protocol generally is a set of agreed conventions (methodology) for handling the exchange of information between communication/processing "elements".

In a wireless medium, the capacity to accommodate multiple users seeking access to the medium must take into account fundamental limitations of bandwidth. For any wireless data communications system there is a finite data carrying capacity, and this capacity must be shared between users on an appropriate basis to satisfy the user's requirements. A number of MAC protocols have been devised for this purpose. Such protocols variously attempt to satisfy the objective of providing users with access to the full medium during times of low load demand, and fair access to the medium during times of high load demand. Furthermore, it may be desirable to guarantee a user the ability to transmit or receive a burst of data on demand regardless of other user load demands.

Usually, users requesting access to a wireless medium will require low reception delays and high throughput. Where wireless data communication services are supplied on a subscription basis, the subscribing users negotiate certain guaranteed performance requirements that have to be met in order for the service provider to retain that subscriber's loyalty.

Known protocols fall broadly within four classes: fixed access, random access, guaranteed access, and hybrid protocols.

The fixed access category includes those MAC protocols where each station is allocated a fixed proportion of the available bandwidth. This category includes time division multiple access (TDMA), frequency division multiple access (FDMA) and code division multiple access (CDMA) protocols. The main problem with fixed access protocols is that they are not flexible enough to efficiently meet the dynamic bandwidth

requirements of a local area network (LAN) environment. Additionally, such a protocol could not be operated as the sole access method, as the bandwidth allocation must be established initially, and re-established when mobile stations move between wireless areas.

A random access protocol is only statistical in its nature and therefore its performance is never guaranteed. There are many examples of random access protocols including those based on ALOHA, Carrier Sense Multiple Access (CSMA) and collision resolution. Random access protocols can generally be characterised by the following properties. At low aggregate loads, a random access protocol usually provides low delay. At high loads, contention will limit throughput and increase delay. Scheduling of transmission by a random access protocol also is difficult due to the lack of guarantees about access to the wireless medium. Similarly, prioritised access to the wireless medium cannot be ensured. ALOHA protocols also tend to ignore collisions, whereas CSMA protocols tend to try and avoid collisions or limit the length of collisions.

Guaranteed Access Protocols, as the name suggests, guarantee access to the medium, and may be achieved using either distributed or centralised control mechanisms. Examples of guaranteed access protocols include polling protocols, token passing protocols and some collision resolution protocols.

Most practical, implementable wireless MAC protocols are designed as a hybrid of two or more protocols from the previously described categories. This allows a wireless MAC protocol to be tailored more easily to provide a range of services given a particular set of wireless physical layer properties. Hybrid protocols are mostly based on the idea of contention on the wireless medium followed by a reservation that holds the wireless medium for a single station without contention.

R-ALOHA is a hybrid protocol that includes elements of random access protocols and guaranteed access protocols. R-ALOHA is based on slotted ALOHA with regular allocation of slots. If a station is successful in transferring a data unit in a slot then it may reserve the same slot in subsequent frames. Reserved access to future slots reduces contention, thus increasing throughput and reducing delay. R-ALOHA has two unsatisfactory aspects. Firstly, it only allows a station to reserve one slot per frame, which is too inflexible in a LAN environment. Secondly, a station may keep a slot reserved without restriction, which may result in unfairness and long delays.

A variation of R-ALOHA, Packet Reservation Multiple Access (PRMA), solves these problems for voice traffic. PRMA supports periodic data units (voice traffic) and random data units (data traffic). Only periodic data units can reserve the same slot in future frames. Random data units always use slotted ALOHA access. Problems similar to those experienced for R-ALOHA are avoided in two ways. Firstly, periodic data units are buffered only for a limited period before they are transmitted or

discarded, thus reducing the load during congestion. Secondly, stations must give up reservations between talk spurts. PRMA is thus very dependent on the properties of speech for effective operation. Another example of this physical layer dependence is that the frame rate in PRMA is tied to the speech rate.

In a published paper entitled "A Dynamic packet-switching system for Satellite Broadcast Channels", (ICC'75, San Francisco, June 1975) the author Binder describes a TDMA based satellite communication scheme where all stations own a channel (or channels) in a frame structure. The frame may have more channels than those owned by stations. All stations receive each transmitted packet via the satellite. Each packet header includes a reservation for the station's queued packets. Stations which do not have a current reservation will have their owned channel used for reservation access. Each station allocates reservation requests on a round-robin basis. A station with new packets to transmit may regain its owned channel by causing a collision. In the next frame all stations will consider the channel reserved by its owner which can then make a reservation request. A master station generates frame markers and transmits the reservation state. This is used by new stations and stations which have lost a packet and hence the reservation sequence.

There is a problem here, however, with packets received with errors. If the packet contained reservations which were processed by other stations, then the receiving station cannot use the reservation scheme for the rest of the frame. This is hard to distinguish from intentional collisions intended to free an owned channel. In addition, a station must receive what it transmits to detect a purposeful collision.

The Motorola ALTAIR™ system uses a reservation protocol with time multiplexed request and data channels in a slotted frame. The start of the frame contains request slots in which user modules (UM) make requests to a central control module (CM) using slotted ALOHA access with an adaptive transmission probability. The end of the frame contains a series of grant slots, which specify the allocation of data slots in the next frame, and a series of management slots. The middle part of the frame contains data slots from the CM to the UMs and allocated data slots from the UMs to the CM. Control information is distributed through blocks at the start and end of a frame with intervening data slots. The mobile station needs to track where it is in this structure and it will lose considerable efficiency if it has a problem receiving a critical block.

An access request is made by competitive ALOHA in the start control block with no feedback until the end of frame control block. Access slots occur in the midst of a potentially long series of user slots. Any failure to track the user slot sequence will affect a station's throughput and the throughput of any other station it collides with. Bandwidth must be consumed to provide guard time between these slots to allow for variation in clock speed between stations.

A more generic reservation protocol than ALTAIR™ was proposed by International Business Machines Corp. for use as the basis of the IEEE 802.11 Standard. It uses a slotted frame with three sections (A, B and C). Each section is preceded by a variable length header containing management information related to the section, including its length. Section A contains the data units from the hub station to the wireless stations, section B contains data units in reserved slots from the wireless stations to the hub station or other wireless stations and section C contains slots used by the wireless stations to send reservations or short data units using a random access protocol. Requests may be for either asynchronous or isochronous bandwidth.

The IBM protocol (disclosed in U.S. Patent No. 5,384,777, Ahmadi et al, entitled "Adaptive Medium Access Control Scheme for Wireless LAN") recognises the importance of power conservation by specifying that all necessary control information is carried in the header at the start of each section. The header indicates when data units will be sent to a wireless station in section A and when the wireless station has slots allocated in section B. The wireless station may power-down at other times and during section C if it does not need to send any data units. However, this functionality requires real time interpretation of complex variable length headers, making the IBM protocol an unlikely candidate for high speed operation. Problems in common with the ALTAIR™ system also equally apply.

Recently, the IEEE 802.11 Working Group selected a MAC protocol, Distributed Foundation Wireless MAC (DFWMAC), that will form the basis of all future work. DFWMAC is a very complex protocol with a number of optional facilities that are supposed to allow it to operate with a range of physical layer properties. It also has modes of operation that allow it to operate with and without the coordination provided by a hub station.

DFWMAC's fundamental mode of operation is known as a distributed coordination function. It uses a CSMA/CA protocol where a mobile station ensures that the channel is clear for a minimum period before transmission. Priority is implemented by ensuring that the sensing occurs for a minimum period depending on the priority level of the data unit. Thus, DFWMAC assumes that the physical layer supports carrier sensing. To avoid the 'hidden terminal problem', a mobile station may optionally also use an RTS/CTS type protocol similar to MA/CA to ensure that long data units do not collide with each other. To ensure error free operation, data units are immediately acknowledged at high priority. A disadvantage of carrier sensing is the significant time spent listening to determine that the wireless medium is free. Then the radio unit must be switched from receive to transmit, which takes further significant time.

DFWMAC also includes a second mode of operation, known as a point coordination function, which effectively provides a synchronous data unit service. In

this mode, a central hub station divides the bandwidth into a frame consisting of a contention free period and a contention period. During the contention free period, a hub station polls mobile stations on a polling list. The hub station starts a contention free period by sending the first poll at a high priority. The reservation mechanism is entirely unsophisticated: 'send a message during the contention period'. There are no methods to respond to bursty traffic or to attempt to make efficient use of the medium.

U.S. Patent No. 4,970,720, Hiroshi Esaki assigned to Toshiba K K, entitled "A Packet Communication Exchanging Apparatus" describes an even simpler CSMA/CA scheme for wired and wireless LANs. Here a station causes a collision to obtain access to the medium by forcing active stations to delay access attempts.

Disclosure of the Invention

The present invention is directed to overcoming or at least ameliorating one or more of the disadvantages in the prior art. Embodiments described herein specify a medium access control protocol that provides mechanisms to make efficient use of the available wireless transmission capacity while supporting the operation of synchronous and asynchronous communications, with guaranteed performance according to negotiated parameters, between a mobile station and a hub station.

Therefore, the invention broadly discloses a method for controlling communications access between a hub and a plurality of distributed stations over a medium, the method comprising the steps of:

(a) allocating a plurality of channels for data communications between the stations and the hub, the number of channels being at least equal to the number of stations, and each station owning at least one channel, each channel being varyingly in one of an empty-, a reserved-, or an owner-state, and whereby:

(i) the empty-state provides a channel to which any station can have access;

(ii) the reserved-state provides a channel to which a station having made a reservation with the hub, but not owning the channel, can have access; and

(iii) the owner-state provides a channel to which only the owning station has access; and

(b) re-allocating the respective state and/or the number of channels over time on the basis of each station's data requirements.

The invention further discloses a method for controlling communications access between a hub and a plurality of mobile stations via a plurality of channels providing data access therebetween, there being at least as many channels as mobile stations, and the channels being varyingly in one of an empty-, a reserved-, or an owner-state, and whereby:

(i) the empty-state provides a channel to which any station can have access;

(ii) the reserved-state provides a channel to which a station having made a reservation with the hub, but not owning the channel, can have access; and

(iii) the owner-state provides a channel to which only the owning station has access;

the method comprising the steps of re-allocating the respective state and/or the number of channels over time on the basis of each station's data requirements.

The invention yet further discloses a communications system having controlled data access to a medium, the system comprising:

a hub having transceiving means for communication via the medium and data processing means;

a plurality of distributed stations, each having transceiving means for communication with the hub via the medium and data processing means;

and wherein said data processing means of the hub and the stations co-operate to allocate a plurality of channels for data communications between the stations and the hub, the number of channels being at least equal to the number of stations, and each station owning at least one channel, each channel being varyingly in one of an empty-, a reserved-, or an owner-state, and wherein:

(i) the empty-state provides a channel to which any station can have access,

(ii) the reserved-state provides a channel to which a station having made a reservation with the hub, but not owning the channel, can have access, and

(iii) the owner-state provides a channel to which only the owning station has access,

and co-operate to re-allocate the respective state and/or the number of channels over time on the basis of each station's data requirements.

The invention yet further discloses a hub for a communications system, operable to have controlled data access to a medium in co-operation with a plurality of distributed stations, the hub comprising:

transceiving means for communications via the medium; and

data processing means coupled to the transceiving means;

and wherein said data processing means of the hub is operable to allocate a plurality of channels for data traffic between the stations and the hub, the number of channels being at least equal to the number of stations, each channel being varyingly in one of an empty-, a reserved-, or an owner-state, and wherein:

(i) the empty-state provides a channel to which any station can have access,

(ii) the reserved-state provides a channel to which a station having made a reservation with the hub, but not owning the channel, can have access, and

(iii) the owner-state provides a channel to which only the owning station has access,

and further operable to re-allocate the respective state and/or the number of channels over time on the basis of each station's data requirements.

The invention yet further discloses a wireless local area network having a medium access protocol to control access, the network comprising:

a hub having transceiving means for communication via free space paths and data processing means;

a plurality of distributed stations, each having transceiving means for communication with the hub via free space paths and data processing means;

and wherein said data processing means of the hub and the stations co-operate to allocate a plurality of channels for data traffic between the stations and the hub, the number of channels being at least equal to the number of stations, and each station owning at least one channel, each channel being varyingly in one of an empty-, a reserved-, or an owner-state, and wherein:

(i) the empty-state provides a channel to which any station can have access,

(ii) the reserved-state provides a channel to which a station having made a reservation with the hub, but not owning the channel, can have access, and

(iii) the owner-state provides a channel to which only the owning station has access,

and co-operate to re-allocate the respective state and/or the number of channels over time on the basis of each station's data requirements.

Embodiments of the invention have the benefit of simultaneously: (a) guaranteeing a minimum access to the network transmission capacity for each mobile station according to negotiated channel parameters, (b) unreserved capacity can be used by other mobile stations, thereby providing such mobile stations with capacity in excess of a guaranteed minimum, and obtained independent of hub control and without requiring additional complexity in the mobile unit, and (c) provides parameters to maximise the probability of successful transmission by one mobile station in situations of competitive access to a slot, including registration slots and empty slots.

One characteristic of the medium access protocol is that it is demand oriented rather than a requesting type known in the prior art.

Brief Description of the Drawings

Embodiments of the invention now will be described with reference to the accompanying drawings, in which:

Fig. 1 is a schematic block diagram of a wireless system upon which a MAC protocol embodying the invention can be implemented;

Fig. 2 is a schematic block diagram of a wireless LAN system in another embodiment;

Fig. 3 is a schematic block diagram of a wired network system in a further embodiment;

Fig. 4 is a schematic block diagram of a hub station;

Fig. 5 is a schematic block diagram of a mobile/radio station;

Figs. 6 to 9 show the structures of transmission in a wireless cell;

Fig. 10 is a state diagram for timing and scheduling of a hub station;

Figs. 11a-11c show state diagrams for a mobile station; and

Figs. 12 to 15 show graphs of throughput and delay for simulated contention situations.

Description of Preferred Embodiments and Best Modes

NETWORK CONFIGURATION AND ELEMENTS

Fig. 1 shows a simplified form of a wireless system 5, in which a single transceiving hub station 8 facilitates data communications between a number of distributed transceiving mobile stations 9. The mobile stations 9 can be mobile within a cell (not shown) controlled by the hub station 8. The hub station 8 acts to coordinate bidirectional data communications between the mobile stations 9, in the example shown, between stations M1 and M3.

Fig. 2 shows a wireless LAN system 10. Four hub stations (H1-H4) 8 are interconnected via a backbone network, in this case star cabled links 11 connected to a switching unit 6. The star network 11 and switching unit 6 equally can be replaced by another backbone network with different topology, including a ring network, and with different media including wireless. Each hub station 8 has an associated wireless cell 13 within which are located various mobile stations (M1-M7). A computing device 14 also has connection to the network 11, as does a gateway 15 providing access to a generic ISDN network 16. Data communications can be between ones of the mobile stations 9, between a mobile station 9 and the computing device 14, or between a mobile station 9 and another device located on the ISDN network 16. Again, the hub stations 8 act to coordinate the flow of data to and from the mobile stations.

Fig. 3 shows a block diagram of a wired network system 17, upon which a protocol embodying the invention also can be implemented. As previously noted, the invention is not limited to wireless environments. A number of terminals (T1-T5) 9' are in cabled connection 13' with a hub station (H1). The cabled connection 13' has the characteristic that the hub station H1 communicates with the terminals 9' using

broadcast transmissions. The hub station, in turn, can be in cabled connection with a computer 14 and a like hub station (H2) (not shown). The hub station H1 coordinates data communications between the terminals T1-T5 and the computer 14. The arrangement of Fig. 3 is simplified inasmuch as there could be many hub stations and associated terminals, interconnected by a backbone wired or wireless network that provides duplex communication between the hub stations 8'.

In a broad form, it can be considered that a hub station 8 or 8' operates on one set of rules to control access to the medium by a number of stations 9 or 9', or either to each other, or to compatible units accessible via a network 11 attached to the hub station 8 or 8'. The stations 9 or 9' use a different set of rules to respond to the hub station based on their internal states.

As shown in Fig. 4, a number of component blocks for a hub station 8 are provided. These take the form of a network interface 20, a buffer memory 21, a framing, forward error correction (FEC) and modulating section 22, a framing, forward error correction and demodulation section 23, an IF (intermediate frequency) system section 24, a radio receiver 25, a radio transmitter 26, and an antenna 27 which is sufficiently broad in its radiation pattern to illuminate the entire cell 13. The antenna 27 can achieve this result statically or dynamically (with electronic or mechanical beam steering). All these items are connected to, and are operable by, a control and timing section 28. In addition, all are powered by an AC mains or battery operable power supply 29.

Equivalent portions of the mobile station 9 are indicated by a designator having a magnitude higher by 10 in Fig. 5. The mobile station 9 has a battery-powered power supply 39.

Further details concerning a modulation and demodulation implementation, as a form of ensemble modulation, are disclosed in commonly owned U.S. Patent No. 5,487,069 (equivalent to Australian Patent No. 666411 and EP-A-0 599 632) entitled "A Wireless LAN", the contents of which are incorporated herein by cross-reference.

It will be noted that the antenna 37 is preferably a steerable antenna which is electronically steerable by the control and timing section 38 to at least partially direct the transmissions to and from the mobile stations 9 towards the corresponding hub station 8. A suitable antenna for this purpose is that disclosed in commonly owned Australian Patent No. 671214 (equivalent to EP-A-0 632 523 and U.S. Patent No. 5,714,961) entitled "A Steerable Antenna", the contents of which also are hereby incorporated by cross-reference.

Software implementing a MAC protocol embodying the invention resides in the timing and control elements 28,38 of a hub station 8 and mobile station 9 respectively.

A characteristic of the communications medium which is important in the following descriptions is referred to as "capture". This may occur in some embodiments under certain conditions. When multiple mobile stations transmit in the same slot the hub station may receive either:

(a) a garbled data unit which cannot be interpreted; this is called "collision" and no "capture" has occurred, or

(b) a correct data unit where the mobile with the strongest signal has swamped the others; this is "capture".

DATA LINK PROCEDURES

The description of the data link procedures will proceed with reference to the system shown in either Figs. 1 or 2, and particularly wireless communications between a hub station 8 and a mobile station 9.

Fig. 6 shows that access to the cell transmission capacity is divided into slots S that alternate between the up-link (mobile to hub) and the down-link (hub to mobile). Each slot carries a data unit M together with physical layer overheads, as shown in Fig. 7.

Slots are organised into channels. A channel is the set of either down-link (hub to mobile) or up-link (mobile to hub) slots, respectively addressed, to or owned by the same mobile station. Each up-link channel, if allocated to a mobile station, is said to be owned by it.

A hub station uses the down-link both to transfer data units to mobiles and to facilitate medium access control operations in the cell. A hub station transmits data units in one of two classes: (i) management traffic, including invitation to register, and (ii) data traffic.

When there are no mobile stations registered, the hub station data units relate principally to registration. Unregistered mobile stations use a modified ALOHA protocol to deliver registration requests to the hub station. These requests include the station's unique MAC address, called the station-id. This is included in the registration confirmation response from the hub station to avoid 'capture' related problems.

When a mobile station registers it obtains the channel identifier of its "owned" channel from the hub station. The hub station allocates a fraction of the available data transfer time to the new mobile and enters it in a scheduling database. The hub station also allocates data unit storage resources for the mobile.

The hub station transmits data units to a specific mobile by setting the station-id of the mobile in the header of the data unit.

The hub station uses a scheduling algorithm to determine which channel will be allocated for a down-link and for the following up-link. Mobiles use a modified R-ALOHA protocol, along with their internal state, to determine use of the up-link.

Each down-link data unit contains an acknowledgment in its header that the hub station sets if it received a data unit correctly in the last up-link slot. This acknowledgment includes the sending station-id to avoid the problem of the capture effect. Mobile stations use the acknowledgment to determine if the data unit they just transmitted was successfully received by the hub station.

A mobile can negotiate for hub station support to achieve battery conservation. In this case, time-critical prompts will be exclusively directed to this mobile which include controls to allow it to ignore, management and data traffic for a period.

Following registration, a mobile station can request that the hub station adjust the parameters controlling its traffic service characteristics.

A wireless medium is subject to unpredictable variations and occasional loss of transmissions. To reduce the impact of any such loss the control elements of the MAC protocol are distributed in time. Instead of channel access information forming a block part of a frame header, it is distributed through the headers of each slot transmitted by the hub station.

The protocol data units (PDU) are constituted differently for the up-link and down-link. Fig. 8 shows the protocol data unit fields for the down-link, while Fig. 9 shows the protocol data unit fields for the up-link. Tables 1A & 1B describe these fields.

Field	Description
dest-id	Identifier of the destination for the payload
source-id	Identifier of the source of the payload.
type	An identifier for a down link data unit format, additionally distinguishing between data and management payloads.
chan-id	Channel identifier for the following up-link. This is in the range 0 to (max_number_allocated_channels - 1) or registration_chan_id (a known number outside that range)
chan-state	The state of the following up-link slot: empty, owner or reserved (Note: the registration channel is always in empty-state)
up-link_result	The result of last up-link transmission as ack or nack.
ack-id	If up-link_result = ack, ack-id is the identifier of the successful source mobile station else unused.
est-num	For the next up-link slot: · For registration: estimated number of registering mobile stations · For data: estimated number of active mobile stations
sleep-num	The duration of sleep following next up-link slot.
payload	· For a data transmission: fixed length data, eg 4 x 53 bytes. · For a management transmission: management data units including beacon, management request and management response.
crc	Data unit integrity check.

Table 1A - Hub station protocol data unit fields

Field	Description
dest-id	Identifier of the destination for the payload
source-id	Identifier of the source of the payload.
type	An identifier for an up link data unit format, additionally distinguishing between data and management payloads.
flow-rq	Flow request for this channel
contend-rq	Request to be counted as a mobile station competing for ALOHA slots.
payload	· For a data channel: fixed length data, eg 4 x 53 bytes · For a management transmission: management data units including registration request, management request and management response.
crc	Data unit integrity check.

Table 1B - Mobile station protocol data unit fields

HUB STATION OPERATION

Operation of the hub station 8 in the wireless cell now will be described with reference to Fig. 10, which is a state machine relating to the timing of the alternating hub-originated and mobile-originated transmission sequence. The process state 40 includes the handling of any received data units from the mobile stations, the processing of acknowledgments, and the generation of the next down link data unit. The transition from the process state 40 to the transmit state 41 is controlled by a slot tick 43 generated by a clock (not shown). Upon completion of a slot transmission, the hub moves to the receive state 42. The hub returns to the process state 40 upon reception of a data unit from a mobile station or after a specified time period.

The transfer of data units out of the wireless cell, ie. to and from a backbone network, may be accomplished asynchronously from the handling of data units to and from the mobiles, and is governed by the protocol on the backbone network.

<u>Hub Cycle</u>

The hub station includes the channel identifier of the next up-link slot in the header part of each down-link slot. Although a channel may be used by any mobile station, priority is given to the mobile station that owns the channel. The sequencing of channels is determined by the 'schedular' process in the hub station taking into account the requirements of each mobile station, including the required service parameters and sleep requirements. Every mobile station registered in a cell is allocated at least one channel. In this way, all mobile stations can be guaranteed some access to the network.

Consecutive up-link and down-link slot pairs are scheduled over a frame. A frame structure is maintained by the hub station and describes the channel sequence for the down-link and the up-link. However, the notion of a frame has no significance outside the hub station, and mobile stations do not need to hold state information about frames. The hub station cycles through the frame structure selecting down-link and up-link channels according to the frame entries.

The information needed to dimension a frame is delivered to the hub station in management requests from the mobiles. The number of slot pairs in a frame is decided dynamically by the hub station, taking into account the number of mobile stations registered in the wireless cell and the type and channel parameters they require. The maximum frame length may be determined by the minimum allowable channel data rate supported by the network. The frame size may change to accommodate mobile station service requirements or changes in the number of mobile stations.

Hub Station Initialisation

The hub station scheduler is initially set for no registered mobiles. In this state, all down-link and up-link slots may be allocated to the management channel, with the intention that they be used for registration.

Hub Registration Process

The registration channel is selected from time to time by the Scheduler. Mobiles use a modified form of slotted-ALOHA to deliver a registration request to the hub station. Failures and successes are used by the hub station to generate an estimate of the number of mobiles attempting to register (see Table 2 below). If the registration succeeds the hub station records the channel identifier for the mobile and informs the Scheduler.

Registration up-link result		**Change to estimated # of registrants**	**Next down-link ack/nack**
Mobile Tx	**Collision**		
no	no	0 (see Note)	nack
yes	yes	+2	nack
yes	no	-1	ack

Note: The absence of any activity for a pre-defined long period of time should result in the estimate being set to zero.

Table 2 - Hub station registration estimation process

The hub station must provide some specific information to the newly registered mobile station. This includes the channel identifier for the first channel to be owned by the mobile station, and other network parameters which will be delivered by management packets.

Hub Channel Operation

The hub station always transmits in down-link slots to mobile stations in a cell. The down-link payload may contain data originating from within the cell, from elsewhere in the network, or from the hub station itself.

Fields in the headers of each down-link slot allocate a channel to the next up-link slot and constrain mobile access to that channel.

Each up-link channel is defined to be in one of three states (empty, reserved or owner). The hub station stores the state of each channel and transmits the state of the next channel (along with other control fields) to the mobile stations in the header field of each down-link slot. The three channel states are defined as follows:

Empty-State

If a data channel is in the empty-state, any mobile station with queued data units is allowed to contend for access to it using a slotted ALOHA protocol. Mobile stations may make reservations for the channel in future frames according to a modified R-ALOHA protocol.

Reserved-State

If a channel is in the reserved-state, the mobile station that has reserved the channel may transmit a data unit. However, the owner of the channel may sometimes use it regardless of the mobile station that has reserved the channel.

Owner-State

If a channel is in the owner-state, only the mobile station that owns the channel may use it to transmit a data unit. Channels allocated to a mobile station with negotiated channel parameters are called "provisioned" and remain in the owner-state. Thus the owner of a channel has guaranteed access.

At the end of each up-link slot the hub station changes the channel state according to the State Table shown in Table 3, and selects the next channel according to a scheduling algorithm.

Provisioned Channel	Up-link State [4]		Up-link Result [4]			Update est-num	Next Channel State	Send ack / nack
	Channel State	Mobile is Owner	Mobile Tx	Collision	Flow Request			
no	empty or reserved [1]	X	yes	yes	X	no	owner	nack
no	" [2]	no	yes	no	res	yes	reserved	ack
no	"	yes	yes	no	own	yes	owner	ack
no	" [3]	X	yes	no	no	yes	empty	ack
no	"	X	no	no	no	no	empty	nack
no	owner	yes	yes	no	own	yes	owner	ack
no	"	X	yes	no	no	yes	empty	ack
no	"	X	no	X	X	no	empty	nack
yes	"	yes	yes	no	X	yes	owner	ack
yes	"	yes	yes	yes	X	no	owner	nack
yes	"	yes	no	no	X	no	owner	nack

Where X = don't care.

Note: 1. Owner pre-emption.

2. Reservation.

3. End of flow.

4. Other states represent protocol error states which may be due to hub station failure, mobile failure or a denial of service attack. The appropriate response may include a hub station restart.

Table 3 - Up-link data channel state transitions

The columns under "Provisioned Channel", "Up-link State" and "Up-link Result" describe the type of the channel, the state of the channel and the result of the latest reception on that channel. The "Update est-num" column indicates whether to use the up-link contend-rq field to update the estimated number of contending mobiles (ie. est-num). In the right hand columns the new state for the channel is given and the "Send ack/nack" column shows what should be sent in the next down-link slot in response to the mobile's data unit.

The hub station is required to acknowledge and to count mobile stations whenever their contend-rq signal indicates that they will be contending for ALOHA slots. The hub station transmits a mobile station estimate in a field in the MAC header part of every down-link.

If a mobile station is to be counted by the hub station then it makes a contend-request in the header part of an up-link slot at the same time it attempts to send a data unit.

The hub must exchange management data units with mobile stations for control tasks which may include registration completion (which might involve security), channel parameter negotiation and sleep control. The channel parameter negotiation may alternatively be delivered by standard signalling procedures.

Hub Station Scheduler

The hub station may enter into contracts with mobile stations to provide certain channel parameters in which it will allocate a portion of the available capacity for the use of that mobile station. The protocol described herein supports guaranteed channel parameter contracts. The hub station supports these contracts with a scheduler that is fair and does not degrade the performance of any existing contracts. The acceptance of a contract requires the allocation of hub station resources up to, but not exceeding, the hub station's total (bandwidth) capacity.

Hub Sleep Scheduling

The protocol described herein supports a mode of operation in which the mobile enters a low-power mode that does not require it to listen to every down-link slot. For a mobile indicating a sleep requirement, the slot scheduler can allocate owned slots during the period when the mobile is awake.

MOBILE STATION OPERATION

A mobile station's operation will be described with reference to Fig. 11.

Mobile cycle

The activity of the mobile station is determined in response to messages received from the hub station. Fig 11a shows that a mobile station operates in three states 'init' 50, 'registration' 51, and 'data' 52. The state 'registration' 51, entered after initialisation or as a result of losing contact with the hub, is expanded in Fig 11b. An unregistered mobile station is in the 'registration-listen' state 53 in which it waits for the hub to issue a registration slot. The mobile enters the 'request-registration' state 54 if it attempts to register. The 'data' state 52 is expanded in Fig 11c. A mobile receives down-link slots from the hub in 'data-receive' state 55. Down-link data units are processed in state 'data-process' 56. Depending on the outcome of the processing, the mobile either exits the 'data' state 52 or enters one of three states: the 'data-transmit' state 57 in which it transmits a data unit in the next up-link slot; the 'data-sleep' state 58 in which it conserves power; or the 'data-receive' state 55.

Mobile Registration

In the 'registration' state 51 shown in Fig. 11a, the mobile operates in accordance with the Registration State Table shown in Table 4 below. The objective of the procedures described by the Registration State Table is to competitively deliver a message to the hub station. The hub station provides an estimate of the number of mobiles it believes are attempting to register. A mobile uses the inverse of this number to set the probability of transmitting its registration request. This is used to increase the probability of a successful registration transmission by delaying, or spreading in time, registration requests of the contending mobile stations.

Channel identifier	**Mobile Tx Probability**	**Result**		**Next Mobile State**
		Mobile Tx	**Hub response**	
registration_chan_id	1/(est-num+1)	yes	nack	registration
registration_chan_id	1/(est-num+1)	yes	ack	data
registration_chan_id	1/(est-num+1)	no	X	registration
other	0	no	X	registration

Table 4 - Mobile registration state table

In Table 4, 'Channel identifier' is the 'chan-id' field in the previous down-link protocol data unit. 'Mobile Tx probability' is used by the mobile station to set the probability that it will attempt to access the channel. The next two columns describe the result of the mobile access attempt: 'Mobile Tx' states whether or not the mobile did attempt to access the channel, and 'Hub response' is the response by the hub station that appears in the down-link slot immediately following the registration attempt and defines whether the registration attempt has succeeded.

Mobile Channel Parameter Request

The mobile station requests channel characteristics consistent with the hub station's scheduling algorithm. The method of delivery of this request to the hub station depends on the networking environment, but can be accomplished though management processing.

Mobile Data Transmission

The following section further describes the operations carried out in the 'data' state 52 of Fig. 11a and its expanded form in Fig. 11c.

The header in an up-link data unit may include a flow request (see Table 1B) that is set by a Mobile station to reserve exclusive access to the channel. The logic to

allow reservations to be made is given in the State Table of Table 5 below. A successful reservation results in a channel being temporarily re-allocated to the mobile station that made the request. This allows the transmission of data in the channel (called a "flow") until the reservation is relinquished by the mobile station dropping the flow request, or the channel is reclaimed by the owner. Two types of "flow" are recorded: owner-flow and reserve-flow.

Current State							Transmission Decision			Flow Record Update			
										Transmission Result			
channel state	mobile has flow in channel	owner	queue length	Flow Request Allowed	Pre-empt Allowed	Release Required	Tx Probability	request flow	increment Flow Counter	ACK & ack-id= station-id	ACK & ack-id≠ station-id	NACK	no Tx
unknown	X	X	X	X	X	X	0						no[d]
empty	X	no	>0	no	X	X	1/(est_num+1)	no	no	no	no	no	no
"	X	no	>0	yes	X	X	1/(est_num+1)	res	no	res	no	no	no
"	X	yes	>0	no	no	X	1/(est_num+1)	no	no	no	no	own	no
"	X	yes	>0	no	yes	X	1	no	no	no	no	own	
"	X	yes	>0	yes	yes	X	1	own	no	own	no	own	
reserved	no	yes	>0	no	yes	X	1	no	no	no	no	own	
"	no	yes	>0	yes	yes	X	1	own	no	own	no	own	
"	yes	no	>0	no	X	X	1	no	yes	no	no	no	
"	yes	no	>0	yes	X	no	1	res	yes	res	no	no	
"	yes	no	>0	yes	X	yes	1	no	yes	no	no	no	
owner	X	yes	>0	no	X	X	1	no	no	no	no	own	
"	X	yes	>0	yes	X	X	1	own	no	own	no	own	
all other cases													no

where d = in addition a down link slot error should be counted,

X = don't care

Table 5 - Mobile data state table

In Table 5, the 'Current state' columns give the state following receipt of a down-link data unit. The 'Transmission decision' columns indicate whether the mobile station should transmit, what flow requests should be made and consequent action. The 'Tx Probability' specifies the probability that the mobile station will transmit. In three cases the transmission probability is determined from the hub station's estimate of the number of mobiles contending for ALOHA access. To compress the table, the Flow Record Update' columns are separated according to whether a transmission was made (first 3 columns) or not (4th column). The first 3 columns specify how the mobile station should update its flow record for each of three possible acknowledgment responses in the next down-link data unit. The action here modifies the flow status of the channel just used. Entry 'no' means that there is no owner or reserve flow and 'res' or 'own' means that 'reserve flow' or 'owner flow' respectively is recorded.

Table 5 also specifies that the mobile station should count errored data units, indicated in the table by 'channel state' = 'unknown'. This number can be used to decide when the link has become unreliable and remedial action needs to be taken, ie. a return from 'data' state 52 to the 'registration' state 51 shown in Fig. 11a.

Also, whenever a mobile transmits it sets its contend-rq field according to Table 6 to assist the hub station in its determination of the number of mobiles contending for empty slots.

Queue length	Contend-Rq
> 1	yes
≤ 1	no

Table 6 - Mobile station Contend-Rq Generation

Owner Flow Requests:

An owner-flow request is a flow request made by a mobile station for a channel that it owns. On receipt of an owner flow request the hub station changes the channel state to owner, meaning only the owner of the channel is allowed access to the channel. This facility allows the owner of a channel to dynamically create a contention free TDMA-like channel for its own use. Even if the hub station does not receive the slot containing the owner-flow request correctly, due to a collision or other error, the request is still successful because the hub station assumes that the owner of the channel has caused the collision to regain access to the channel. This state will not persist unnecessarily as the owner must request retention of owner-state in successive slots.

An owner-flow request must receive a positive acknowledgment with the owner ack-id to be considered successful. A mobile station that makes an owner-flow request marks the channel as an owner flow and increments "Flows", a counter in each

mobile station that represents the total number of flows that the mobile station currently holds. Similarly, the end of a flow must result in "Flows" being decremented.

A mobile station will make an owner-flow request for a channel only if the data in its queue cannot be transmitted in the flows that the mobile station has already been granted.

Reserve Flow Requests:

A reserve-flow request is a flow request made by a mobile station for any channel that it does not own. If the slot containing a reserve-flow request is correctly received by the hub station, it changes the channel state to reserved-state.

If the slot containing the reserve-flow request is not correctly received by the hub station it is assumed that the owner of the channel has caused a collision in order to regain access to the channel. The hub station changes the channel state to owner-state, which is the same action as for incorrectly received slots containing an owner-flow request.

A mobile station making a reserve-flow request must wait for an explicit acknowledgment, with the ack-id matching the station-id (to avoid the "capture" problem) that the request was received correctly by the hub station before marking the channel as a reserve-flow and incrementing "Flows". The acknowledgment to the reverse-flow request is controlled in the header of the next down-link slot.

A mobile station should make a reserve-flow request for a channel only if the data in its queue cannot be transmitted in the flows that the mobile station has already been granted. Specifically, there must be potential to transmit all data using just one access to each of the granted flows.

After a mobile station receives a down-link data unit it must use its current state, shown in the Current State columns of Table 5 and Table 6, to decide whether and how it is going to transmit a data unit in the next up-link slot. The mobile station's Current State consists of:

"Channel State" - the state of the channel determined by the hub station.

"Mobile has flow in chan" - indicates if a reserve-flow or owner-flow is recorded for the channel.

"Owner" - indicates that the Mobile station owns the channel.

"Queue Length" - the number of data unit payloads in the Mobile station's queue.

FlowRequestAllowed = (QueueLength > Flows+1).

Pre-emptAllowed = (Queue Length > Flows).

ReleaseRequired = (FlowCounter = 0).

Given a particular current state, the appropriate action is shown in the transmission decision columns in Table 5. If the "Tx Probability" is one, the mobile station always transmits. If the "Tx Probability" is zero, then the mobile station must not transmit a data unit. If a data unit is transmitted then the "request reserve-flow" and "request owner-flow" columns indicate whether a "reserve-flow request" or an "owner-flow request" respectively should be made.

A parameter, "FlowMax" is defined and a counter "FlowCounter" is required in each mobile station. Every time a mobile station transmits a data unit in a reserve-flow, the mobile station increments "FlowCounter" modulus "FlowMax". The value of "FlowMax" is a configurable parameter. If "FlowCounter" equals zero when a mobile station is about to transmit a data unit in a reserved-flow, the mobile station must not request continuation of the reserved-flow irrespective of the state of its queue or the number of other flows it currently holds. A mobile station never has to release an owner-flow because they are not considered to be part of the sharing process.

In general terms, low values for FlowMax are always unsatisfactory as they limit throughput, while large values give good throughput but poor delay. A broad range of intermediate values can provide good performance.

The "increment FlowCounter" column of Table 5 indicates whether "FlowCounter" should be incremented modulus "FlowMax".

The transmission result block in Table 5 shows the action that is taken after reception of the next down-link slot that may contain an acknowledgment of any data unit transmitted.

Mobile Sleeping

A battery powered mobile station may wish to remove power from some parts of its electronic circuitry whenever its operation is not required, and thus can enter the 'data-sleep' state 58 shown in Fig. 11c. This is supported by the Hub station's scheduling process.

Performance Data

Negotiated access by stations can be scheduled without contention and with delays agreed upon. The remaining traffic involves contended access to the network, including traffic subject to statistical multiplexing. This contended traffic has been the subject of simulation.

Two independent methods were used to perform the simulation. The result shown here were derived from a software implementation of the protocol using the C programming language. In this simulation the hub and mobile stations, were each implemented as a thread, where all communications among them were restricted to information in the packet exchanges illustrated in Figs. 11. The traffic used in the simulations was generated using Poisson statistics. The base simulation unit was a time-slot, instead of absolute time in seconds, as a result the performance illustrated is valid for arbitrary slot sizes.

These simulation results were verified using a commercial simulation package, called OPNET, supplied by MIL 3, Inc, 3400 International Drive, Washington D.C. 20008.

Figs. 12-15 variously have as an indices 'Offered Load' vs 'Throughput', where a value of 1 indicates the whole part of the bandwidth available for non-guaranteed traffic and 'Delay' vs 'Throughput'. The channel may have scheduling agreements for, say, 90% of its capacity, with the remaining 10% being subject to contention.

Figs. 12 and 13 show the situation of ten mobile stations competing with equal probability for network access. The hub does round-robin scheduling of the ten slots owned by the stations.

The throughput plot shows that the protocol is converting the Offered Load directly to throughput over almost the entire range. Also shown on Fig. 12 is additional protocol-related traffic required to obtain competitive access. This region between "data" and "data+collision" shows increasing activity as the probability of slotted ALOHA type collisions increases as load increases, then a progressive reduction as the protocol's behaviour becomes more TDMA like. The delay remains better than that achieved in pure TDMA, conventionally taken to be 1+ (no. slots /2), in this case 6 slots, until the offered load reaches 0.3. Then it increases as collisions cause delayed access. However this still stays quite low until the offered load approaches 0.9. At this point mean delay grows rapidly because a TDMA mode of operation is not uniformly established and where collision is still being used to obtain access queue length (hence delay) will increase.

Figs. 14 and 15 relate to a simulation where there are again ten stations being offered their owner slots on a round-robin basis.

However, one station (causing "heavy" traffic) is generating 90% of the system's Offered Load while the other nine stations (causing "light" traffic) evenly share the remaining 10% of the Offered Load. Note that there are no traffic agreements here. The Offered Loads are still for the contended part of the system bandwidth only.

The system Throughput directly matches the Offered Load up to an Offered Load of around near 0.8. The "heavy" traffic station will attempt to use all the slots it requires while "light" traffic stations will increasingly need to collide to temporarily reserve their owned slots to deliver a packet. The region representing collisions shows this behaviour. As the system load becomes high, the "light" station will need to use nearer and nearer to 10% of the channel. To obtain this they will consume an increasing part of the bandwidth in collisions. So, after reaching a peak, throughput will decline as collisions become more likely. As the decision to transmit is probabilistic, even the (data + collision Throughput) cannot reach 1.

At the same time, the "heavy" station will have increasing difficulty emptying its queue and its delay increases sharply. On the other hand, the "light" stations can regain their owned channel and dispatch their packets before another arrives. Figs. 13 and 15 show very good Delay performance.

This demonstrates excellent fairness, in that the heavy user did not prevent stations with modest requirements from using the network.

Embodiments of the invention provide advantages (or avoid disadvantages) over the prior art MAC hybrid protocols discussed earlier. In relation to R-ALOHA, the present MAC protocol attempts to reserve multiple slots depending on how many data units have been buffered. However, it does not retain reserved slots beyond its immediate need to use them or beyond the specified consecutive number of accesses. Also, in comparison with R-ALOHA there is an improvement in performance by stations owning channels which can be preempted on demand, where the demand includes collision of transmission, and also by structuring uplink and downlink slots so as to provide immediate feedback to a previous transmission attempt. In relation to the PRMA protocol, the present protocol, in contrast, does not distinguish between "voice" and "other" traffic, in which case there is no reliance on characteristics of voice traffic, such as freedom to discard data units, or relatively fixed frame rates. The technique of obtaining access to reserved slots has been enhanced by the concept of "owner channel" which may be rapidly forced into a reserved-state rather than waiting for an ALOHA access to succeed.

Turning now to the ALTAIR™ system, for the present protocol control information is distributed in time and each slot access is controlled by the previous slot header and acknowledged by the following slot header. Failure to read one of the control messages will result in the loss of only one slot access, which is a small impact. Further, the present protocol uses a number of schemes to generate access, including the guaranteed reservation, thereby obviating the need for complex feedback. Finally, the present protocol allows mobile stations to respond directly to hub station messages, in that there is no requirement to determine when a granted slot number occurs. There

also is no requirement for accurate timing by the mobile stations. Rather, only the hub station's timing is important to avoid unwanted unused time.

Turning now to the IBM protocol, the same observations over and above in relation to ALTAIR™ apply, together with the added advantage that the present protocol is less complex as there is a less involved overall structure and powering down is directed by the hub station.

Turning finally to the DFWMAC protocol, in comparison, the present protocol has the ability to respond to bursty traffic and to make efficient use of the available medium. Furthermore, the protocol is able to specify when a mobile station may sleep because of the defined centralised control, which otherwise is more difficult to achieve in a distributed control system.

While the wireless LAN and wired network embodiments have been described, the invention has numerous other applications, including the following.

The MAC protocol can be used to control the resources in a wireless LAN where a number of computers, some of which may be mobile, are connected to each other and/or a wired backbone LAN. The MAC protocol could also be used to control access to a wireless access point for an ATM network, commonly referred to as wireless ATM. This could be for the access of mobile of fixed computer terminals to an ATM network or for connecting together physically separated ATM networks.

Another area of application is the delivery of entertainment services, Internet and telephony services to the home or office. This could be using coaxial cable systems, hybrid fibre coaxial cable systems, hybrid fiber-radio systems or fiber to the kerb followed by radio or Copper wire-based access to the home or office. In these applications, the MAC protocol is used to control access to and from a home/office, but particularly on the so-called back channel (transmission from the home/office to the head-end) where a number of users share the same bandwidth for data and/or telephony.

The MAC protocol can have further applications in radio based personal communications systems where both voice and data traffic is generated by mobile handsets or terminals.

The MAC protocol can have further applications in point to multi-point radio communications systems where a number of stations are communicating to a central station which may be connected to a communications network. Such systems may be used in wireless back-hand for mobile communications networks such as trunked radio or Group Speciale Mobile (GSM).

A yet further application is for wireless systems in homes or offices for the distribution of entertainment services and data between a set-top box provided by a service provider to a number of televisions, and/or computers and associated peripherals.

It is possible to extend the MAC protocol to include the establishment of peer to peer networks. These are networks where there is no controlling hub station, but a collection of mobile terminals which wish to communicate amongst themselves. These extension enable communications to occur. Alternatively, it may be possible to have a mobile terminal(s) with hardware and software to enable it to operate as a hub station using this MAC protocol.

CLAIMS:

1. A method for controlling communications access between a hub and a plurality of distributed stations over a medium, the method comprising the steps of:

(a) allocating a plurality of channels for data communications between the stations and the hub, the number of channels being at least equal to the number of stations, and each station owning at least one channel, each channel being varyingly in one of an empty-, a reserved-, or an owner-state, and whereby:

(i) the empty-state provides a channel to which any station can have access;

(ii) the reserved-state provides a channel to which a station having made a reservation with the hub, but not owning the channel, can have access; and

(iii) the owner-state provides a channel to which only the owning station has access; and

(b) re-allocating the respective state and/or the number of channels over time on the basis of each station's data requirements.

2. A method as claimed in claim 1, wherein the data communication is over a medium having finite bandwidth.

3. A method as claimed in claim 1 or claim 2, wherein there are at least as many channels in the owner-state as there are stations.

4. A method as claimed in any one of the preceding claims, comprising the further step of a station at any time requesting of the hub to be allocated one or more extra channels.

5. A method as claimed in any one of the preceding claims, whereby a channel further provides for management traffic between each station and the hub, and comprises the further step, as management traffic, of a station negotiating with the hub to be allocated a required number of channels in the owner-state.

6. A method as claimed in claim 5, comprising the further step of a station negotiating with the hub to be allocated a required number of channels in the reserved-state.

7. A method as claimed in either one of claims 5 or 6, comprising the further steps of a station requesting an indication of the number of stations seeking to

register, and the hub responding thereto, wherein said station receives said indication by request and indication.

8. A method as claimed in either one of claims 5 or 6, comprising the further steps of a station requesting an indication of the number of stations seeking to register, and the hub responding thereto, wherein said station receives said indication by broadcast.

9. A method as claimed in any one of claims 5 to 8, comprising the further steps of a station requesting an indication of the number of stations seeking to use a channel and the hub responding thereto, whereby said station receives said indication by request and indication.

10. A method as claimed in any one of claims 5 to 8, comprising the further steps of a station requesting an indication of the number of stations seeking to use a channel and the hub responding thereto, whereby said station receives said indication by broadcast.

11. A method as claimed in any one of claims 5 to 10, comprising the further step of a station requesting the hub to be deregistered to give-up allocated channels.

12. A method as claimed in any of claims 5 to 10, comprising the further step of a station requesting the hub to delay any data communication to the station for a period of time to be in a sleep mode.

13. A method as claimed in any one of the preceding claims, whereby the step of re-allocation includes the step of temporarily ascribing use of reserved-state channel to a non-owning station.

14. A method as claimed in claim 13, whereby said temporary use is rescinded following lapse of a time period of no use by the ascribed station.

15. A method as claimed in either one of claims 12 or 13, whereby the owning station of said reserved-state channel resumes use on demand.

16. A method as claimed in any one of the preceding claims, whereby each said channel comprises a plurality of slots and each slot comprises a data unit of varying length, and wherein each channel has either hub-to-mobile slots or mobile-to-

hub slots, and comprising the further step of the length of hub-to-mobile slots being arranged to be different from the length of the mobile-to-hub slots.

17. A method as claimed in claim 16, whereby the length of said hub-to-mobile slots is different from the length of said mobile-to-hub slots, and comprising the further step of the length of the slots being varied to account for different traffic conditions.

18. A method as claimed in claim 17, whereby in the slot length varying step, the hub is configured to replace a mobile-to-hub slot with a hub-to-mobile slot to account for different traffic conditions.

19. A method for controlling communications access between a hub and a plurality of mobile stations via a plurality of channels providing data access therebetween, there being at least as many channels as mobile stations, and the channels being varyingly in one of an empty-, a reserved-, or an owner-state, and whereby:

(i) the empty-state provides a channel to which any station can have access;

(ii) the reserved-state provides a channel to which a station having made a reservation with the hub, but not owning the channel, can have access; and

(iii) the owner-state provides a channel to which only the owning station has access;

the method comprising the steps of re-allocating the respective state and/or the number of channels over time on the basis of each station's data requirements.

20. A method as claimed in claim 19, wherein the data communication is over a medium having finite bandwidth.

21. A method as claimed in either one of claims 19 or 20, whereby a channel further provides for management traffic between each station and the hub, and comprises the further step, as management traffic, of a station negotiating with the hub to be allocated a required number of channels in the owner-state.

22. A method as claimed in any one of claims 19 to 21, wherein the medium is free space.

23. A method as claimed in any one of claims 19 to 22, comprising the further step of a station negotiating with the hub to be allocated a required number of channels in the reserved state.

24. A method as claimed in any one of claims 19 to 22, comprising the further steps of a station requesting an indication of the number of stations seeking to register, and the hub responding thereto, wherein said station receives said indication by request and indication.

25. A method as claimed in any one of claims 19 to 23, comprising the further steps of a station requesting an indication of the number of stations seeking to register, and the hub responding thereto, wherein said station receives said indication by broadcast.

26. A method as claimed in any one of claims 19 to 25, comprising the further steps of a station requesting an indication of the number of stations seeking to use a channel, and the hub responding thereto, wherein said station receives said indication by request and indication.

27. A method as claimed in any one of claims 19 to 25, comprising the further steps of a station requesting an indication of the number of stations seeking to use a channel, and the hub responding thereto, wherein said station receives said indication by broadcast.

28. A method as claimed in any one of claims 19 to 27, comprising the further step of a station requesting the hub to be deregistered to give-up allocated channels.

29. A method as claimed in any one of claims 19 to 28, comprising the further step of a station requesting the hub to delay any data communications to the station for a period of time to be in a step mode.

30. A method as claimed in any one of claims 19 to 29, whereby the step of reallocation includes the step of temporarily ascribing use of reserved-state channel to a non-owning station.

31. A method as claimed in claim 30, whereby said temporary use is rescinded following lapse of a time period of no use by the ascribed station.

32. A method as claimed in either one of claims 30 or 31, whereby the owning station of said reserved-state channel resumes use on demand.

33. A method as claimed in any one of claims 19 to 32, whereby each said channel comprises a plurality of slots and each slot comprises a data unit of varying length, and wherein each channel has either hub-to-mobile slots or mobile-to-hub slots, and comprising the further step of the length of hub-to-mobile slots being arranged to be different from the length of the mobile-to-hub slots.

34. A method as claimed in claim 33, whereby the length of said hub-to-mobile slots is different from the length of said mobile-to-hub slots, and comprising the further step of the length of the slots being varied to account for different traffic conditions.

35. A method as claimed in claim 34, whereby in the slot length varying step, the hub is configured to replace a mobile-to-hub slot with a hub-to-mobile slot to account for different traffic conditions.

36. A communications system having controlled data access to a medium, the system comprising:

a hub having transceiving means for communication via the medium and data processing means;

a plurality of distributed stations, each having transceiving means for communication with the hub via the medium and data processing means;

and wherein said data processing means of the hub and the stations co-operate to allocate a plurality of channels for data communications between the stations and the hub, the number of channels being at least equal to the number of stations, and each station owning at least one channel, each channel being varyingly in one of an empty-, a reserved-, or an owner-state, and wherein:

(i) the empty-state provides a channel to which any station can have access,

(ii) the reserved-state provides a channel to which a station having made a reservation with the hub, but not owning the channel, can have access, and

(iii) the owner-state provides a channel to which only the owning station has access,

and co-operate to re-allocate the respective state and/or the number of channels over time on the basis of each station's data requirements.

37. A system as claimed in claim 36, wherein the stations are mobile and the medium is free space.

38. A system as claimed in either one of claims 36 or 37, wherein the data communications is over a medium having finite bandwidth.

39. A system as claimed in any one of claims 36 to 38, wherein there are at least as many channels in the owner-state as there are stations.

40. A system as claimed in any one of claims 36 to 39, wherein a station data processing means, at any time, requests from the hub data processing means to be allocated one or more extra channels.

41. A system as claimed in any one of claims 36 to 40, wherein the hub data processing means further provides for management traffic between each station and the hub, and the management traffic includes a station negotiating with the hub to be allocated a required number of channels in the owner-state.

42. A system as claimed in claim 41, wherein a station data processing means negotiates with the hub data processing means to be allocated a required number of channels in the reserved-state.

43. A system as claimed either one of in claims 41 or 42, wherein a station data processing means requests an indication of the number of stations seeking to register, and the hub data processing means responds thereto, and wherein said station receives said indication by request and indication.

44. A system as claimed either one of in claims 41 or 42, wherein a station data processing means requests an indication of the number of stations seeking to register, and the hub data processing means responds thereto, and wherein said station receives said indication by broadcast.

45. A system as claimed in any one of claims 41 to 44, wherein a station data processing means requests an indication of the number of stations seeking to use a channel and the hub responding thereto, and wherein said station receives said indication by request and indication.

46. A system as claimed in any one of claims 41 to 43, wherein a station data processing means requests an indication of the number of stations seeking to use a channel and the hub responding thereto, and wherein said station receives said indication by broadcast.

47. A system as claimed in any one of claims 41 to 46, wherein a station data processing means requests the hub data processing means to be deregistered to give-up allocated channels.

48. A system as claimed in any one of claims 41 to 47, wherein a station data processing means requests the hub data processing means to delay any data communication to the station for a period of time to be in a sleep mode.

49. A system as claimed in any one of claims 36 to 48, wherein re-allocation includes temporarily ascribing use of reserved-state channel to a non-owning station.

50. A system as claimed in claim 49, wherein said temporary use is rescinded following lapse of a time period of no use by the ascribed station.

51. A system as claimed in either one of claims 49 or 50, wherein the owning station of said reserved-state channel resumes use on demand.

52. A system as claimed in any one of claims 36 to 51, whereby each said channel comprises a plurality of slots.

53. A system as claimed in claim 52, whereby each slot comprises a data unit of varying length.

54. A system as claimed in either one of claims 52 or 53, whereby each channel comprises either hub-to mobile slots or mobile-to-hub slots.

55. A system as claimed in claim 54, whereby the length of said hub-to-mobile slots is different from the length of said mobile-to-hub slots.

56. A system as claimed in any one of claims 52 to 54, whereby the length of said slots varies to account for different traffic conditions.

57. A system as claimed in any one of claims 54 to 56, whereby the hub is configured to replace a mobile-to-hub slot with a hub-to-mobile slot to account for different traffic conditions.

58. A hub for a communications system, operable to have controlled data access to a medium in co-operation with a plurality of distributed stations, the hub comprising:

transceiving means for communications via the medium; and

data processing means coupled to the transceiving means;

and wherein said data processing means of the hub is operable to allocate a plurality of channels for data traffic between the stations and the hub, the number of channels being at least equal to the number of stations, each channel being varyingly in one of an empty-, a reserved-, or an owner-state, and wherein:

(i) the empty-state provides a channel to which any station can have access,

(ii) the reserved-state provides a channel to which a station having made a reservation with the hub, but not owning the channel, can have access, and

(iii) the owner-state provides a channel to which only the owning station has access,

and further operable to re-allocate the respective state and/or the number of channels over time on the basis of each station's data requirements.

59. A hub as claimed in claim 58, wherein the stations are mobile and the medium is free space.

60. A hub as claimed in either one of claims 58 or 59, wherein the data communications is over a medium having finite bandwidth.

61. A hub as claimed in any one of claims 58 to 60, wherein there are at least as many channels in the owner state as there are stations.

62. A hub as claimed in any one of claims 58 to 61, wherein a station data processing means, at any time, requires from the hub data processing means to be allocated one or more extra channels.

63. A hub as claimed in any one of claims 58 to 62, wherein the hub data processing means further provides for management traffic between each station and the hub, and the management traffic includes a station negotiating with the hub to be allocated a required number of channels in the owner-state.

64. A hub as claimed in any one of claims 58 to 63, wherein a station processing means negotiates with the hub data processing means to be allocated a required number of channels in the reserved-state.

65. A hub as claimed in claim 63 or 64, wherein a station data processing means requests an indication of the number of stations seeking to register, and the hub data processing means responds thereto, and wherein said station receives said indication by request and indication.

66. A hub as claimed in claim 63 or 64, wherein a station data processing means requests an indication of the number of stations seeking to register, and the hub data processing means responds thereto and wherein said station receives said indication by broadcast.

67. A hub as claimed in any one of claims 63 to 66, wherein a station data processing means requests an indication of the number of stations seeking to use a channel, and the hub responding thereto, and wherein said station receives said indication by request and indication.

68. A hub as claimed in any one of claims 63 to 66, wherein a station data processing means requests an indication of the number of stations seeking to use a channel, and the hub responding thereto, and wherein said station receives said indication by broadcast.

69. A hub as claimed in any one of claims 63 to 67, wherein a station data processing means requests the hub data processing means to be deregistered to give up allocated channels.

70. A hub as claimed in any one of claims 63 to 69, wherein a station data processing means requires the hub data processing means to delay any data communication to the station for a period of time to be in a sleep mode.

71. A hub as claimed in any one of claims 59 to 70, wherein re-allocation includes a temporarily ascribing use of reserved-state channel to a non-owning station.

72. A hub as claimed in claim 71, wherein said temporary use is rescinded following laps of a time period of no use by the ascribed station.

73. A hub as claimed in either one of claims 71 or 72, wherein the owning station of said reserved-state channel resumes use on demand.

74. A method as claimed in any one of claims 58 to 73, whereby each said channel comprises a plurality of slots.

75. A hub as claimed in claim 74, whereby each slot comprises a data unit of varying length.

76. A hub as claimed in either one of claims 74 or 75, whereby each slot is owned by a station.

77. A hub as claimed in any one of claims 74 to 76, whereby each channel comprises either hub to mobile slots or mobile to hub slots.

78. A hub as claimed in claim 77, whereby the length of said hub-to-mobile slots is different from the length of said mobile-to hub-slots.

79. A hub as claimed in any one of claims 74 to 78, whereby the length of said slots varies to account for different traffic conditions.

80. A hub as claimed in any one of claims 77 to 79, whereby the hub is configured to replace a mobile-to-hub slot with a hub-to-mobile slot to account for different traffic conditions.

81. A wireless local area network having a medium access protocol to control access, the network comprising:

a hub having transceiving means for communication via free space paths and data processing means;

a plurality of distributed stations, each having transceiving means for communication with the hub via free space paths and data processing means;

and wherein said data processing means of the hub and the stations co-operate to allocate a plurality of channels for data traffic between the stations and the hub, the number of channels being at least equal to the number of stations, and each station owning at least one channel, each channel being varyingly in one of an empty-, a reserved-, or an owner-state, and wherein:

(i) the empty-state provides a channel to which any station can have access,

(ii) the reserved-state provides a channel to which a station having made a reservation with the hub, but not owning the channel, can have access, and

(iii) the owner-state provides a channel to which only the owning station has access,

and co-operate to re-allocate the respective state and/or the number of channels over time on the basis of each station's data requirements.

82. A wireless local area network as claimed in claim 81, wherein the stations are mobile and the medium is free space.

83. A wireless local area network as claimed in either one of claims 81 or 82, wherein the data communications is over a medium having finite bandwidth.

84. A wireless local area network as claimed in any one of claims 81 to 83, wherein there are at least as many channels in the owner state as there are stations.

85. A wireless local area network as claimed in any one of claims 81 to 84, wherein a station data processing means, at any time, requires from the hub data processing means to be allocated one or more extra channels.

86. A wireless local area network as claimed in any one of claims 81 to 85, wherein the hub data processing means further provides for management traffic between each station and the hub, and the management traffic includes a station negotiating with the hub to be allocated a required number of channels in the owner-state.

87. A wireless local area network as claimed in any one of claims 81 to 86, wherein a station processing means negotiates with the hub data processing means to be allocated a required number of channels in the reserved-state.

88. A wireless local area network as claimed in either one of claims 86 or 87, wherein a station data processing means requests an indication of the number of stations seeking to register, and the hub data processing means responds thereto, and wherein said station receives said indication by request and indication.

89. A wireless local area network as claimed in either one of claims 86 or 87, wherein a station data processing means requests an indication of the number of stations seeking to register, and the hub data processing means responds thereto, and wherein said station receives said indication by broadcast.

90. A wireless local area network as claimed in any one of claims 86 to 89, wherein a station data processing means requests an indication of the number of

stations seeking to use a channel, and the hub responding thereto, and wherein said station receives said indication by request and indication.

91. A wireless local area network as claimed in any one of claims 86 to 87, wherein a station data processing means requests an indication of the number of stations seeking to use a channel, and the hub responding thereto, and wherein said station receives said indication by broadcast.

92. A wireless local area network as claimed in any one of claims 86 to 90, wherein a station data processing means requests the hub data processing means to be deregistered to give up allocated channels.

93. A wireless local area network as claimed in any one of claims 86 to 92, wherein a station data processing means requires the hub data processing means to delay any data communication to the station for a period of time to be in a sleep mode.

94. A wireless local area network as claimed in any one of claims 86 to 93, wherein re-allocation includes a temporarily ascribing use of reserved-state channel to a non-owning station.

95. A wireless local area network as claimed in claim 94, wherein said temporary use is rescinded following laps of a time period of no use by the ascribed station.

96. A wireless local area network as claimed in either one of claims 94 or 95, wherein the owning station of said reserved-state channel resumes use on demand.

97. A wireless local area network as claimed in any one of claims 81 to 96, whereby each said channel comprises a plurality of slots.

98. A wireless local area network as claimed in claim 97, whereby each slot comprises a data unit of varying length.

99. A wireless local area network as claimed in either one of claims 97 or 98, whereby each channel comprises either hub-to-mobile slots or mobile-to-hub slots.

100. A wireless local area network as claimed in claim 99, whereby the length of said hub-to-mobile slots is different from the length of said mobile-to-hub slots.

101. A wireless local area network as claimed in any one of claims 97 to 100, whereby the length of said slots varies to account for different traffic conditions.

102. A wireless local area network as claimed in any one of claims 99 to 101, whereby the hub is configured to replace a mobile-to-hub slot with a hub-to-mobile slot to account for different traffic conditions.

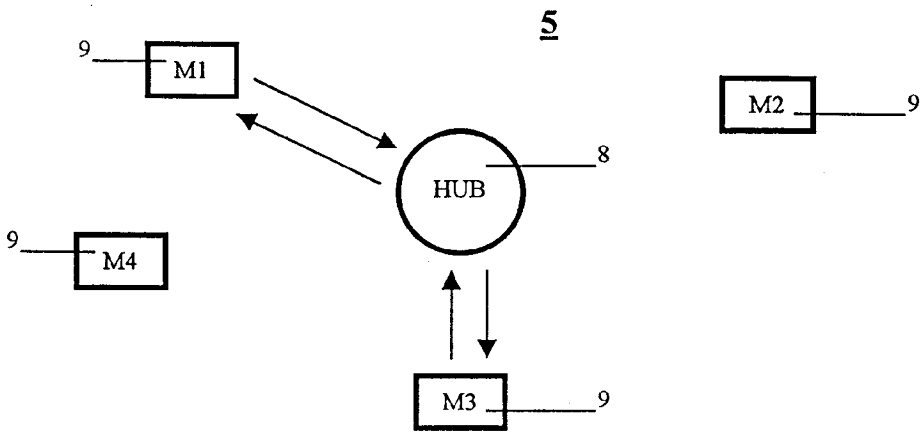
5
M1
9
M2
9
HUB
8
M4
9
M3
9

Fig.1

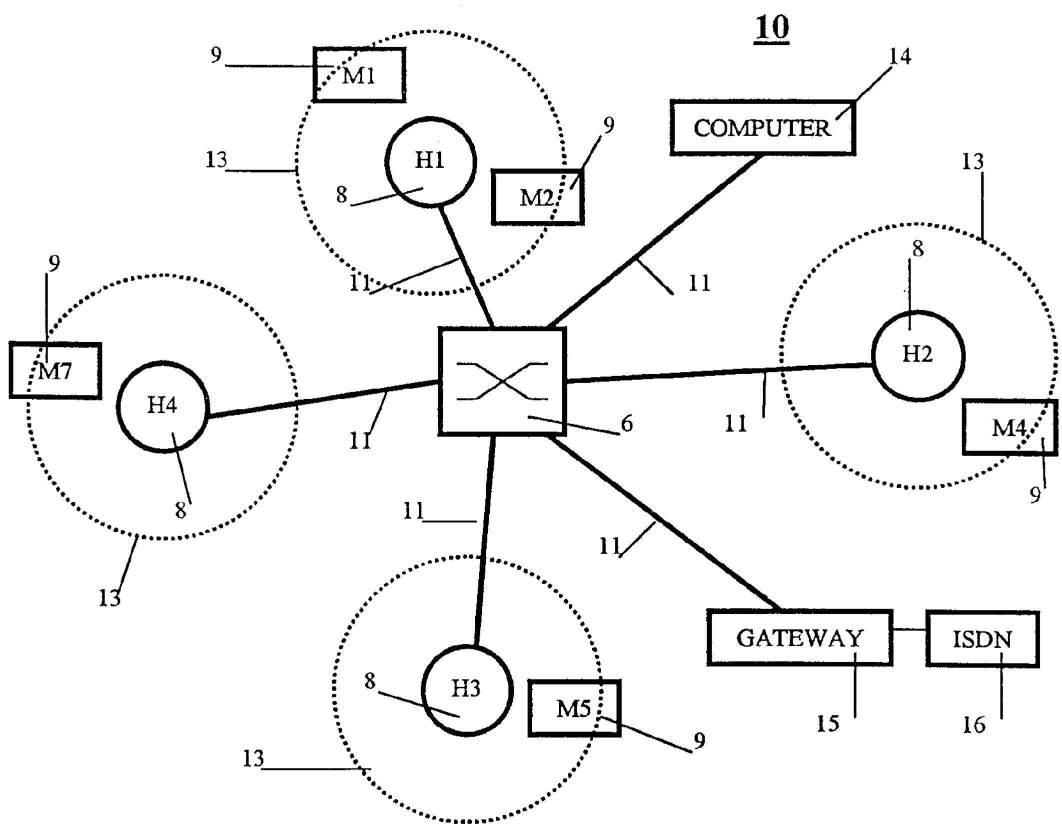
10
M1
9
14
COMPUTER
13
H1
9
M2
8
13
8
9
11
11
M7
H4
H2
6
11
11
M4
9
8
11
11
13
GATEWAY
ISDN
H3
M5
8
9
13
15
16

Fig.2

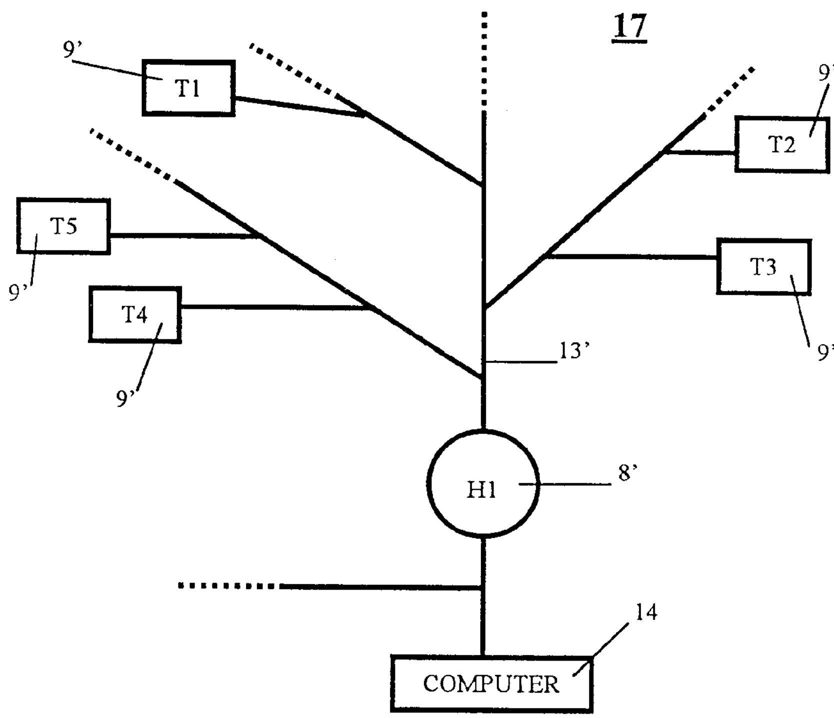

Fig.3

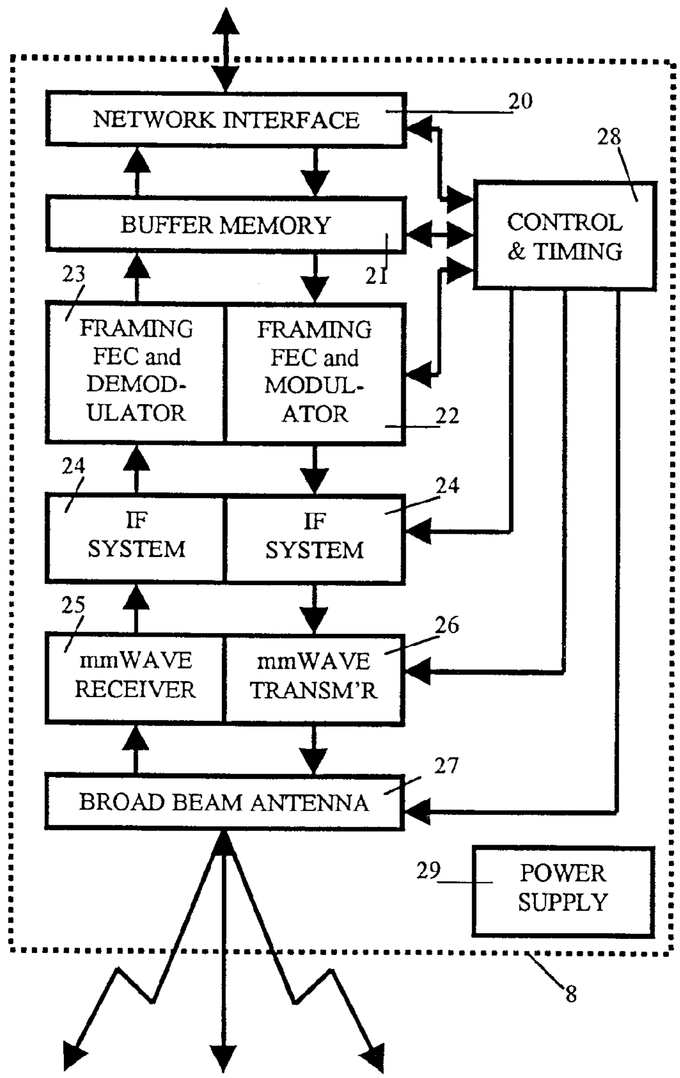
NETWORK INTERFACE
20
28
BUFFER MEMORY
CONTROL
& TIMING
23
21
FRAMING
FEC and
DEMOD-
ULATOR
FRAMING
FEC and
MODUL-
ATOR
22
24
24
IF
SYSTEM
IF
SYSTEM
25
26
mmWAVE
RECEIVER
mmWAVE
TRANSM'R
27
BROAD BEAM ANTENNA
29
POWER
SUPPLY
8

Fig.4

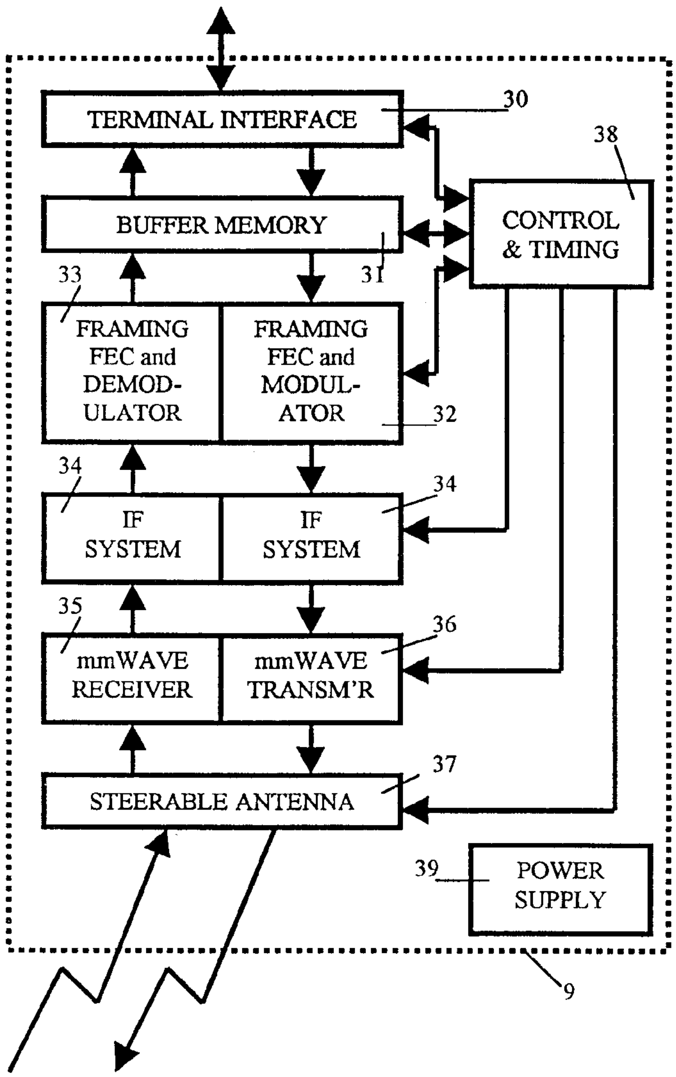
TERMINAL INTERFACE
30
38
BUFFER MEMORY
CONTROL & TIMING
33
31
FRAMING FEC and DEMOD-ULATOR
FRAMING FEC and MODUL-ATOR
32
34
IF SYSTEM
IF SYSTEM
34
35
mmWAVE RECEIVER
mmWAVE TRANSM'R
36
37
STEERABLE ANTENNA
39
POWER SUPPLY
9

Fig.5

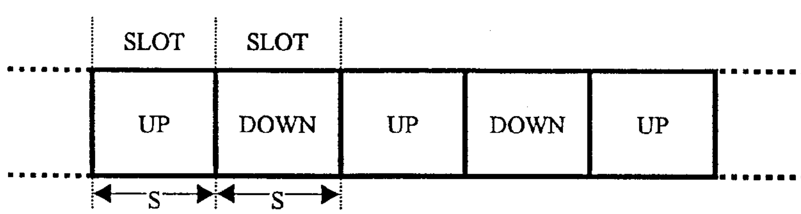
SLOT
SLOT
UP
DOWN
UP
DOWN
UP
S
S

Fig.6

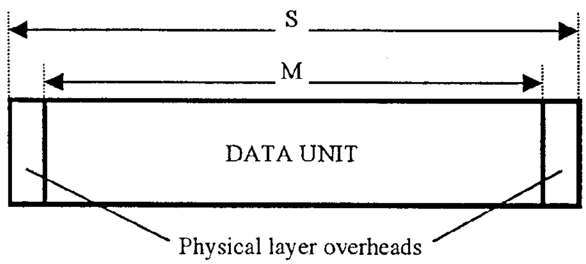

Fig.7

HUB DATA UNIT

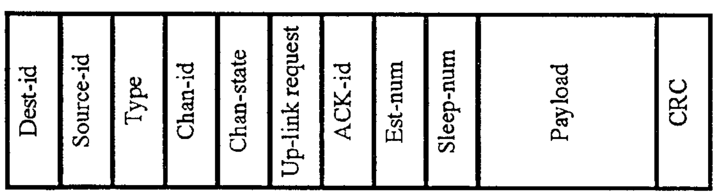

Fig.8

MOBILE DATA UNIT

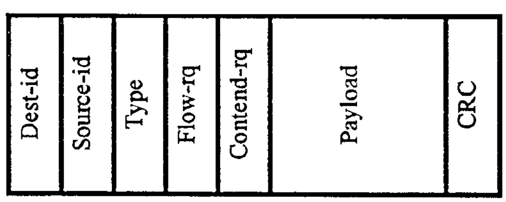

Fig.9

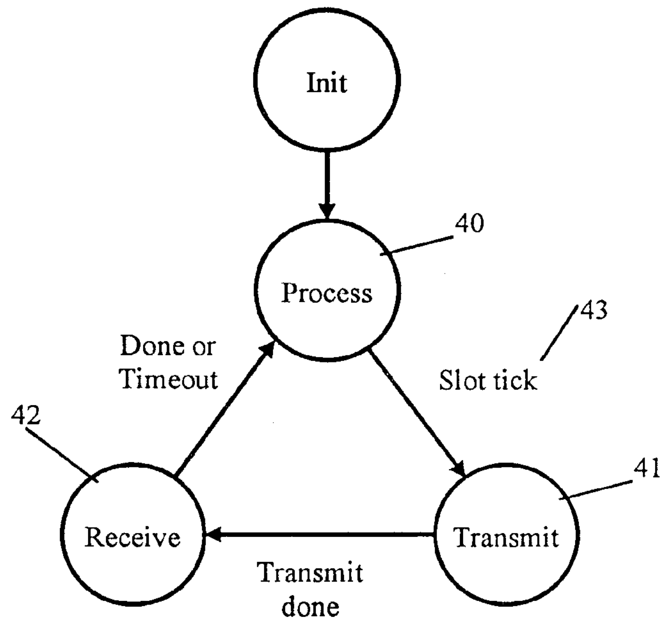

Fig.10

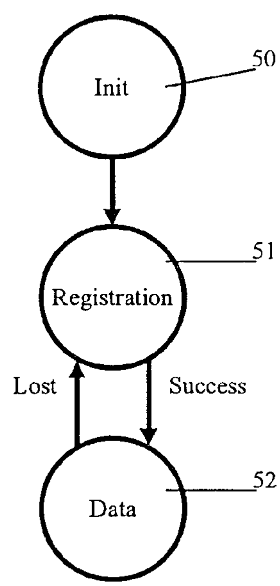

Fig.11a

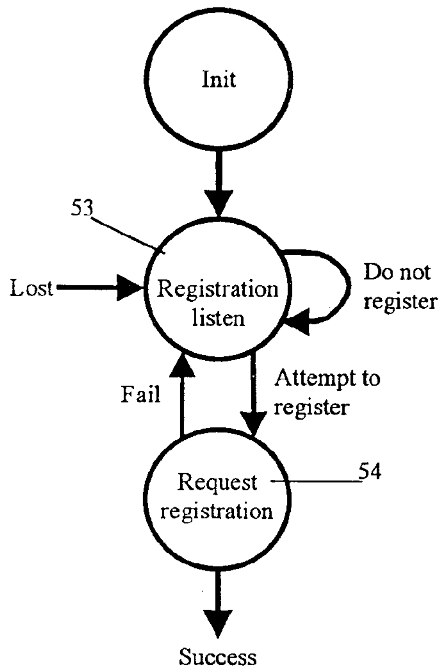

Fig.11b

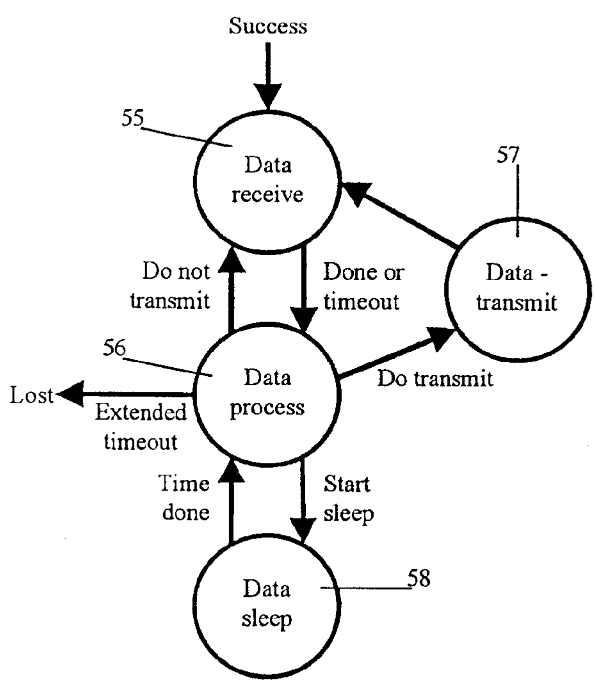

Fig.11c

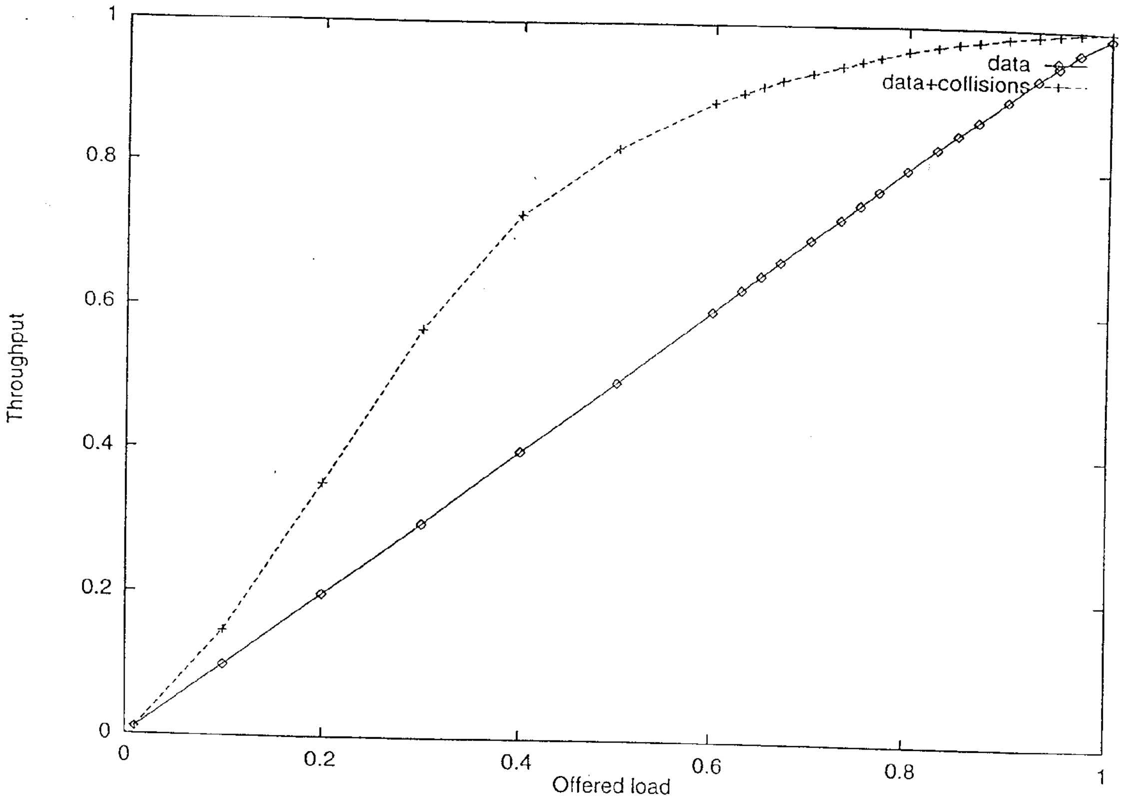

FIG. 12

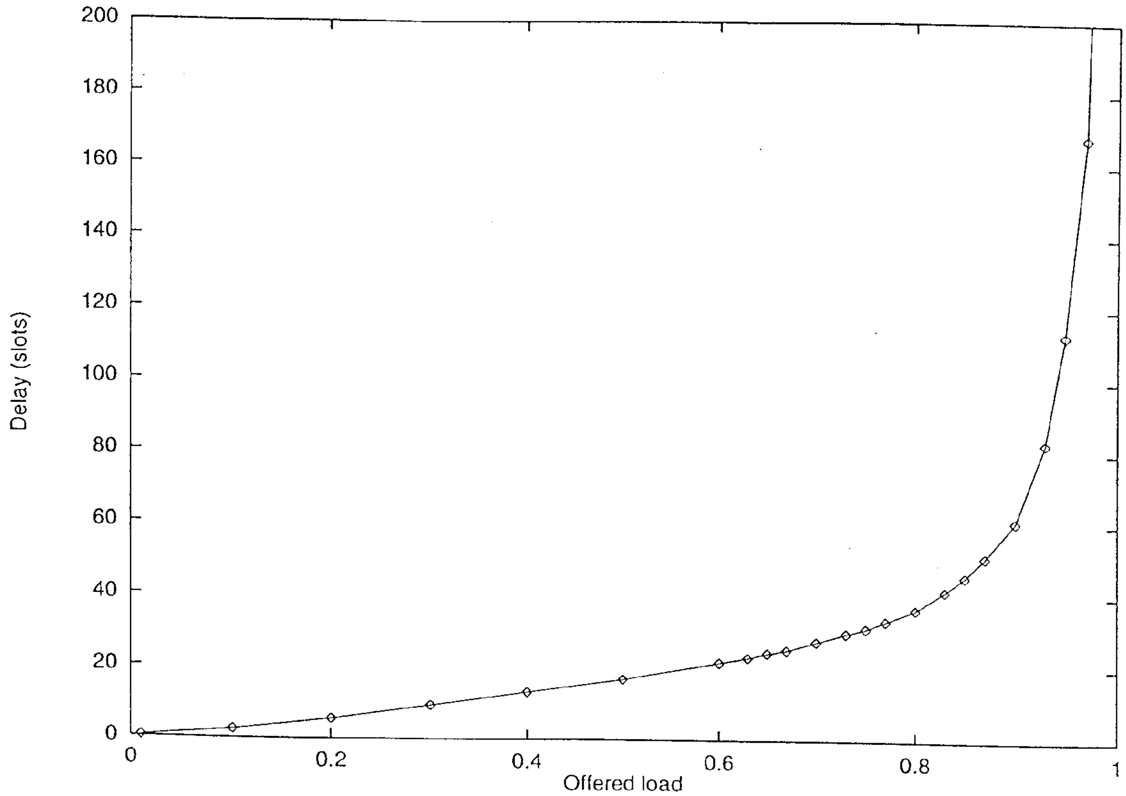
Delay (slots)
200
180
160
140
120
100
80
60
40
20
0
0
0.2
0.4
0.6
0.8
1
Offered load

FIG. 13

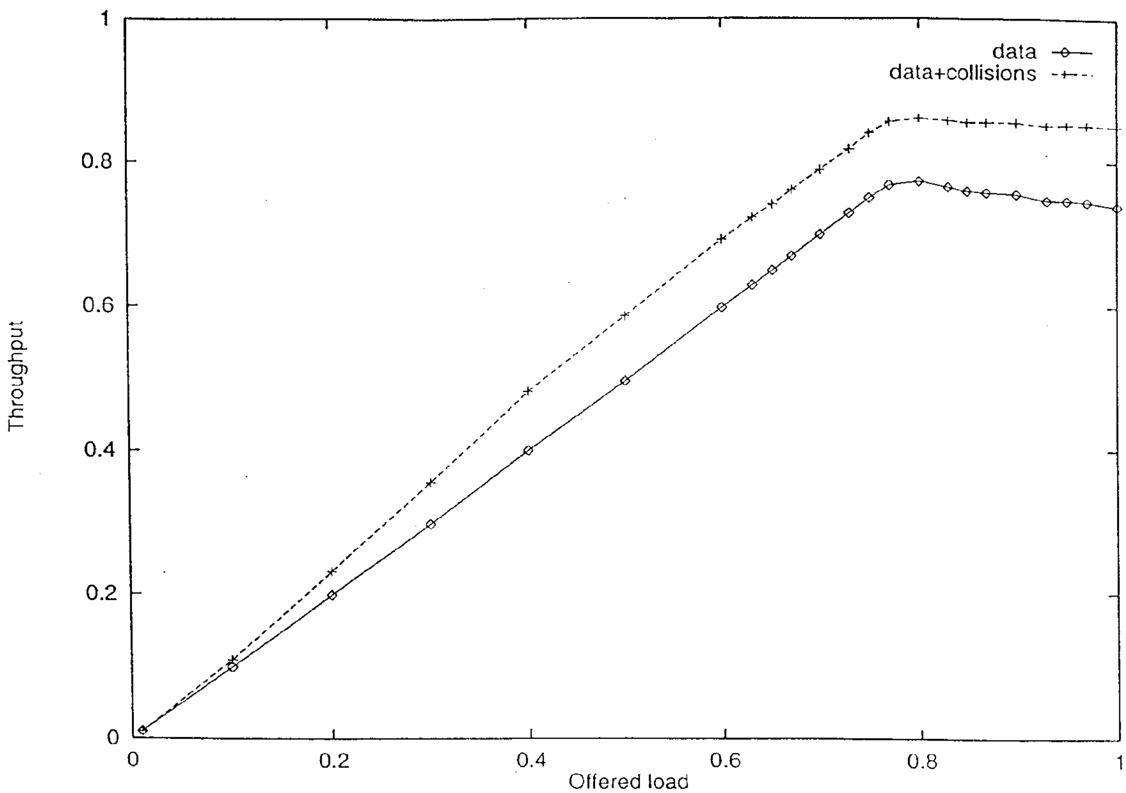

FIG. 14

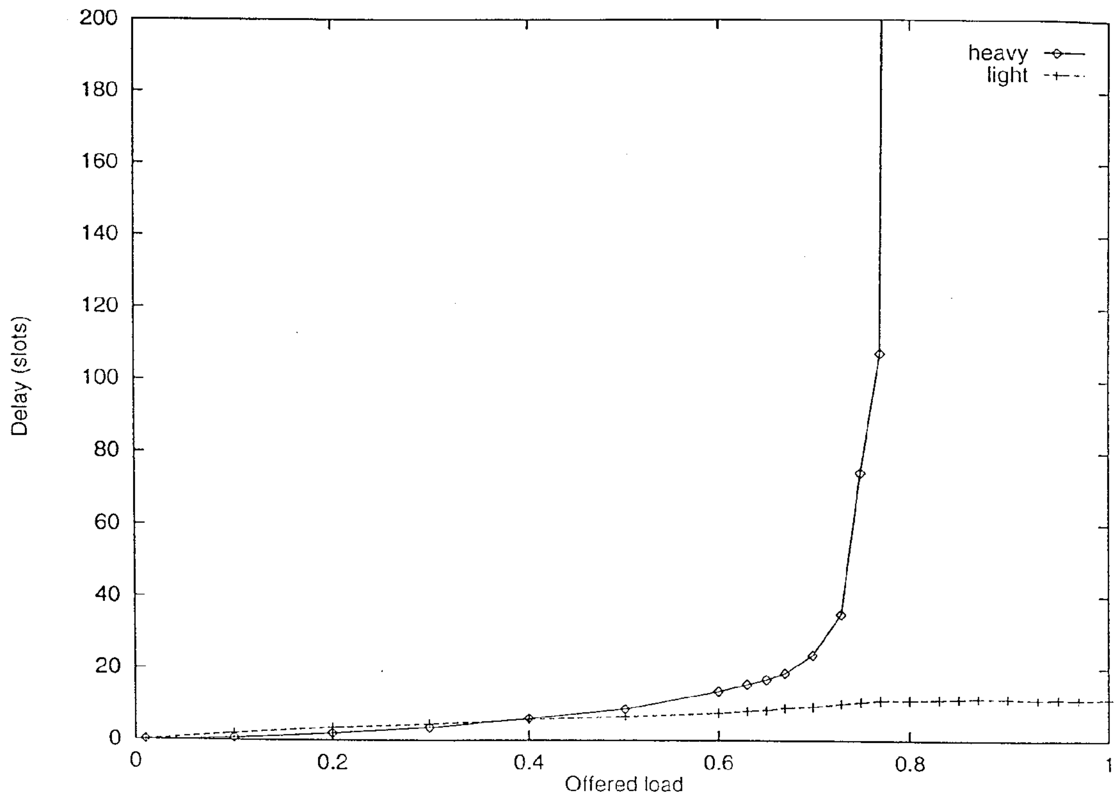
heavy
light
Delay (slots)
200
180
160
140
120
100
80
60
40
20
0
0
0.2
0.4
0.6
0.8
1
Offered load

FIG. 15

INTERNATIONAL SEARCH REPORT

International application No.
PCT/AU 98/00785

A.	**CLASSIFICATION OF SUBJECT MATTER**
Int Cl^{6}:	H04L 12/403, 29/08
According to International Patent Classification (IPC) or to both national classification and IPC	

B.	**FIELDS SEARCHED**
Minimum documentation searched (classification system followed by classification symbols)	
IPC:	H04L; H04Q; H04B; G06F
Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched	
AU:	IPC as above
Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)	
1 WPAT :	WIRELESS; LAN; RESERV; HUB; PROTOCOL; ALOHA; (MEDIUM, ACCESS)
2 INSPEC :	

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	WO 96/31077 A (TELEFONAKTIEBOLAGET LM ERICSSON) 3 October 1996 whole document	1-102
A	US 5436902 A (McNAMARA et al) 25 July 1995 whole document	1-18;36 to 57; 58-80
A	EP 06538652 A (INTERNATIONAL BUSINESS MACHINES) 17 May 1995 whole document	19-35;81-102

[X] Further documents are listed in the continuation of Box C

[X] See patent family annex

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
7 October 1998	16 OCT 1998

Name and mailing address of the ISA/AU	Authorized officer
AUSTRALIAN PATENT OFFICE PO BOX 200 WODEN ACT 2606 AUSTRALIA Facsimile No.: (02) 6285 3929	**MR ATA MAQBOOL** Telephone No.: (02) 6283 2183

INTERNATIONAL SEARCH REPORT

.ernational application No.
PCT/AU 98/00785

C (Continuation).	**DOCUMENTS CONSIDERED TO BE RELEVANT**	
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 5384777 A (AHMADI et al) 24 January 1995 whole document	1-102

INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.
PCT/AU 98/00785

This Annex lists the known "A" publication level patent family members relating to the patent documents cited in the above-mentioned international search report. The Australian Patent Office is in no way liable for these particulars which are merely given for the purpose of information.

Patent Document Cited in Search Report		Patent Family Member					
WO	96/31077	AU	52914/96	CA	2216400	CN	1185265
		NO	974488	SE	9501177		
US	5436902	WO	95/27356				
EP	653865	CA	2103134	EP	653865	JP	7193585
		US	5502724				
US	5384777	BR	9401518	CA	2115211	CN	1100857
		EP	621708	JP	7015433		

END OF ANNEX